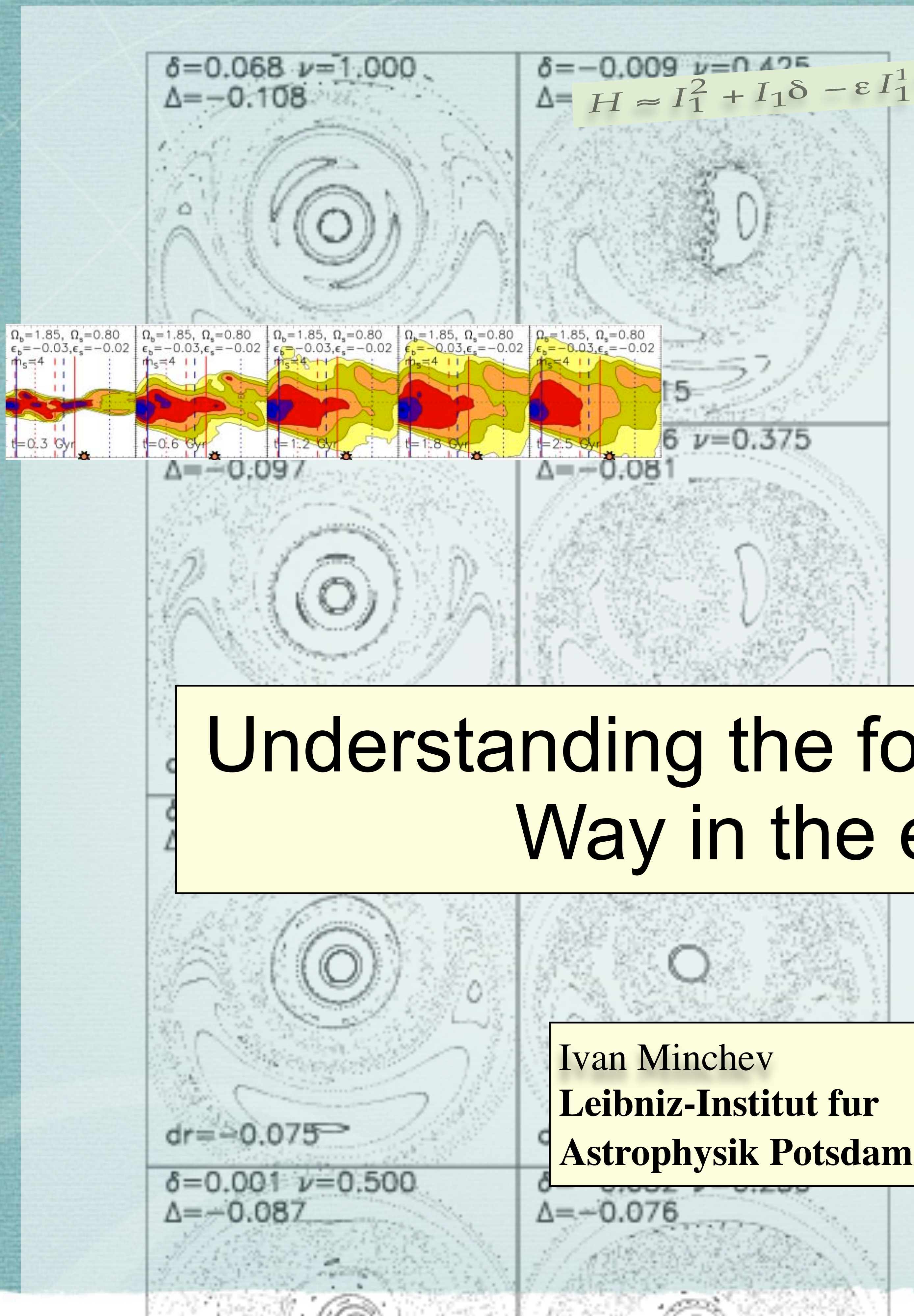


$$H \approx I_1^2 + I_1\delta - \varepsilon I_1^{1/2}\cos\phi \; - \beta I_1^{1/2}\cos[\phi + \nu t + \gamma]$$

Understanding the formation of the Milky Way in the era of Gaia

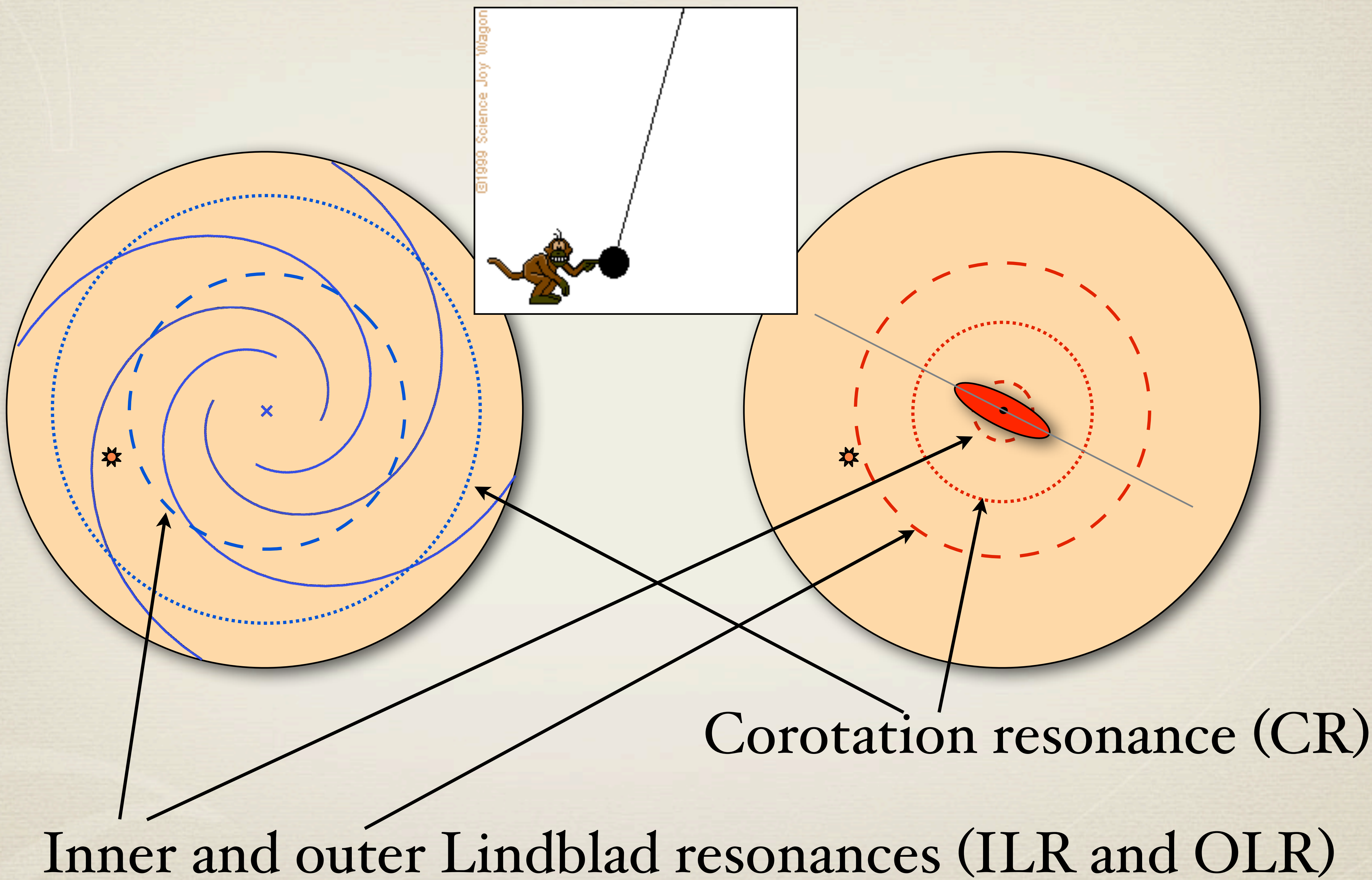
Ivan Minchev
Leibniz-Institut fur Astrophysik Potsdam (AIP)

AIP
Leibniz-Institut für Astrophysik Potsdam

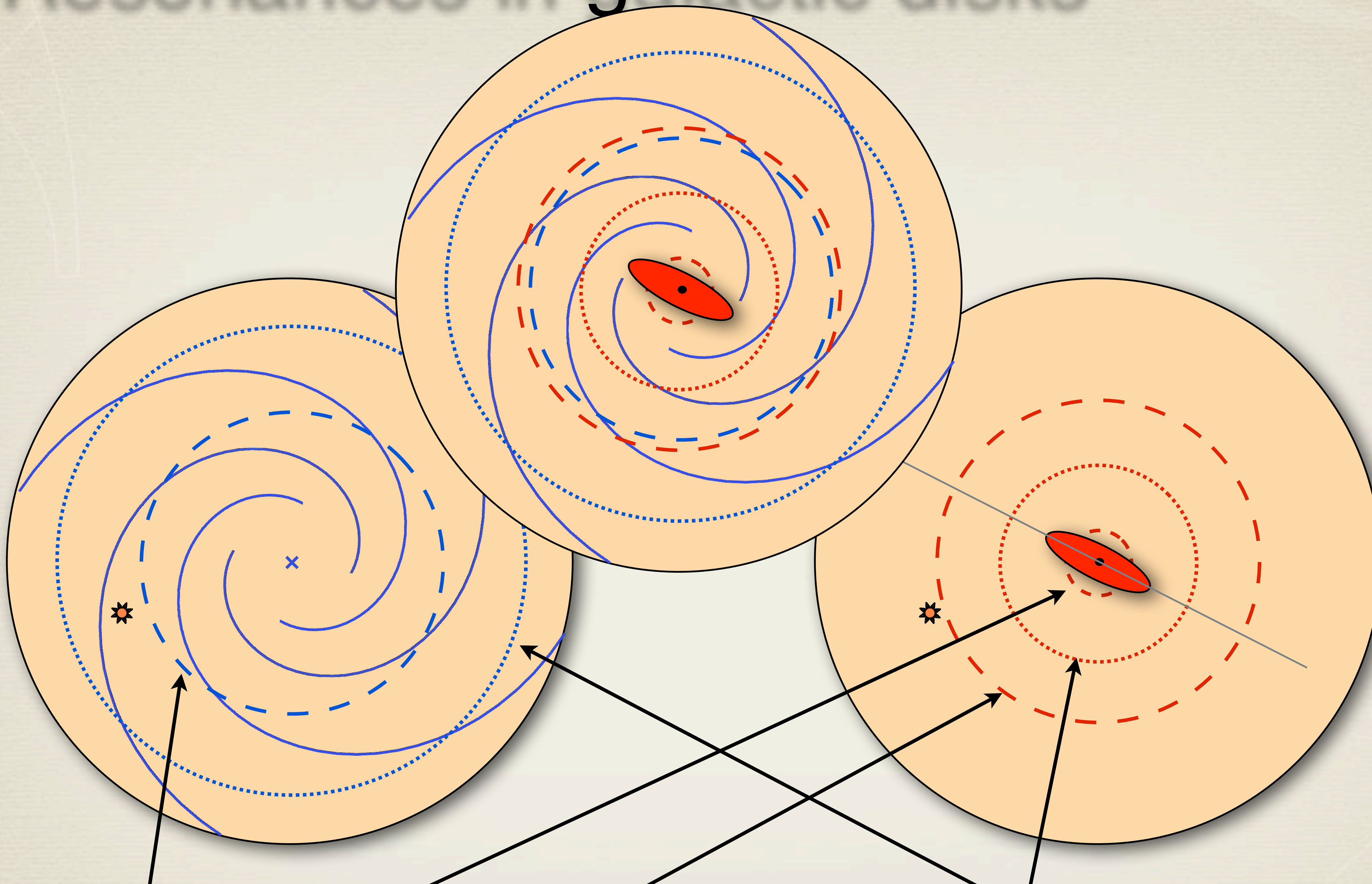
Talk outline

- Effect of disk asymmetries (bars, spirals) on stellar orbits.
- Radial migration in galactic disks.
- Our chemo-dynamical model (Minchev, Chiappini & Martig 2013, 2014).
- On the formation of galactic thick disks.

Resonances in galactic disks



Resonances in galactic disks

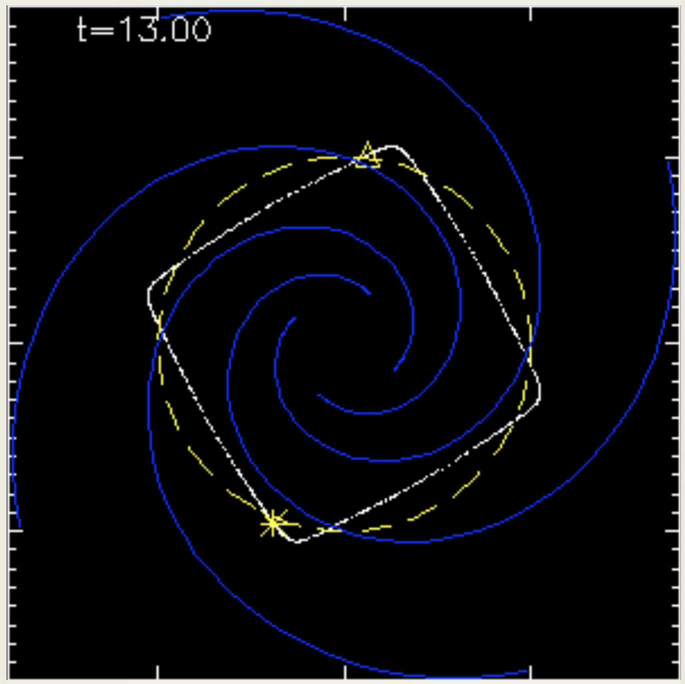


Corotation resonance (CR)

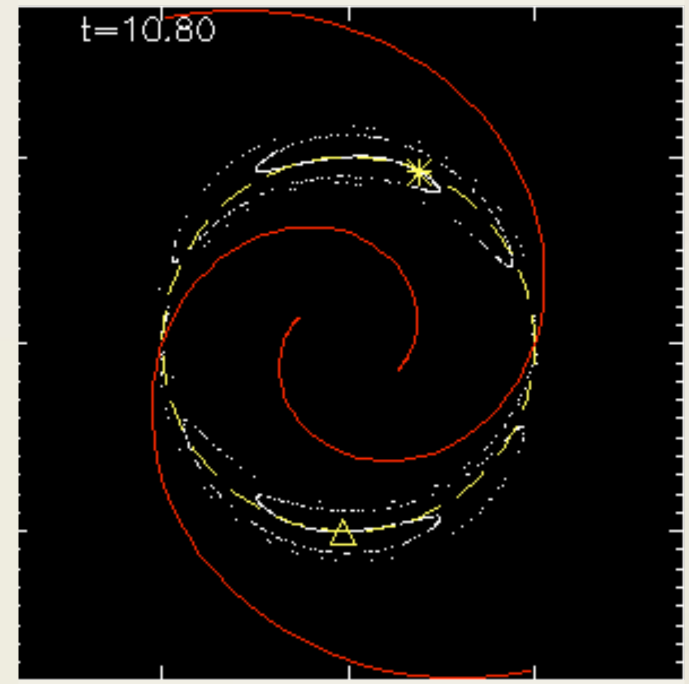
Inner and outer Lindblad resonances (ILR and OLR)

Stellar orbits near resonances

Near OLR

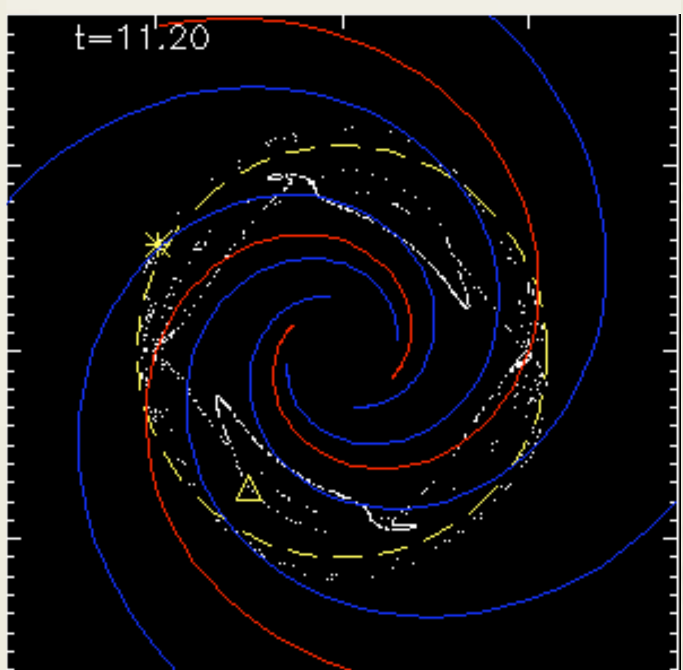


Near Corotation (CR)

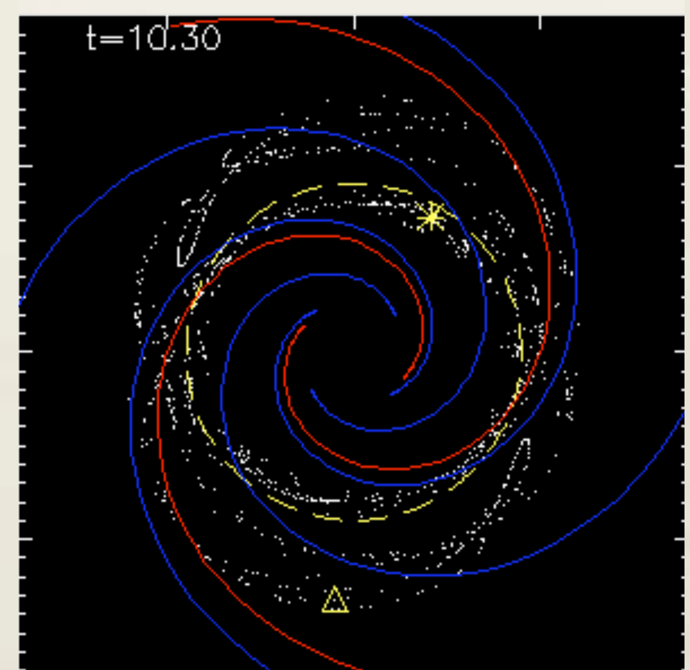


Single spiral wave

Outside OLR+CR

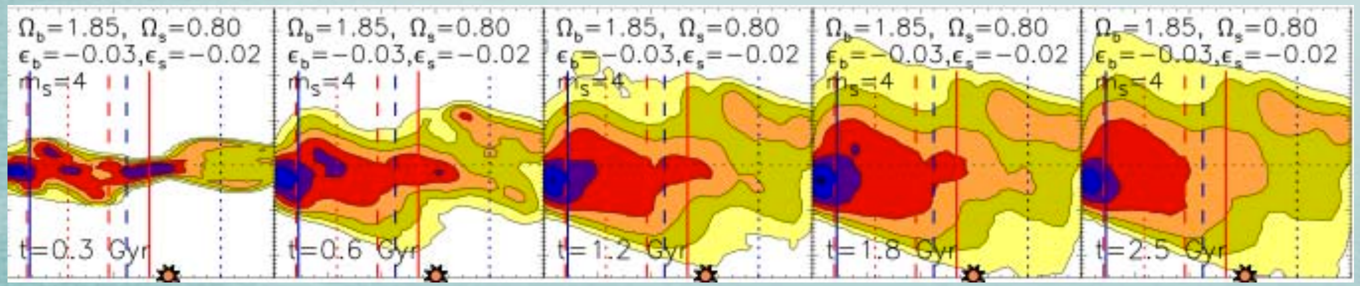


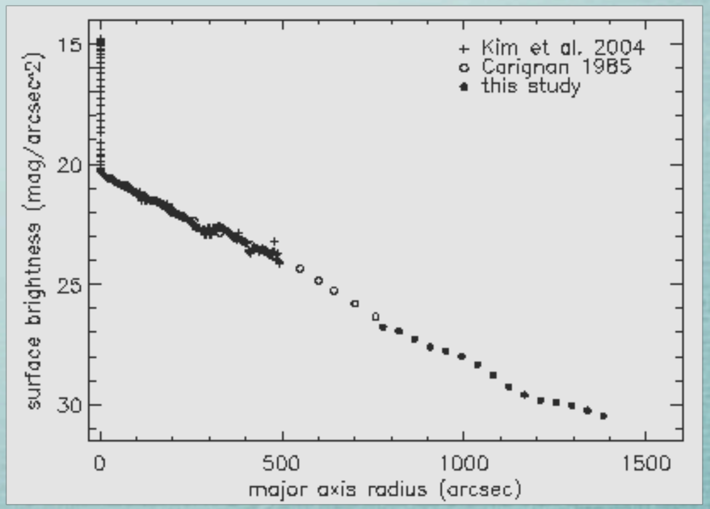
Inside OLR+CR



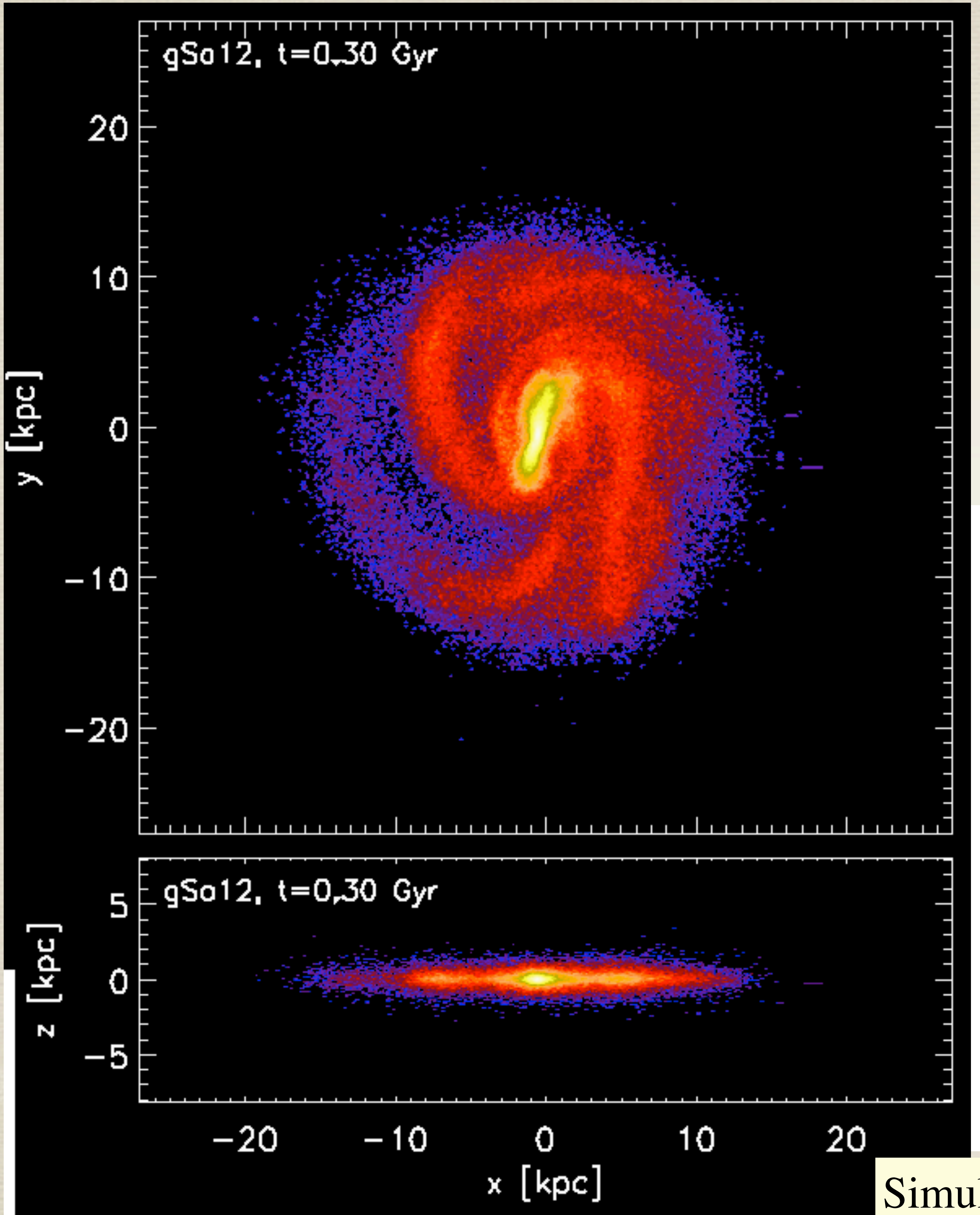
2 spiral waves

Radial migration

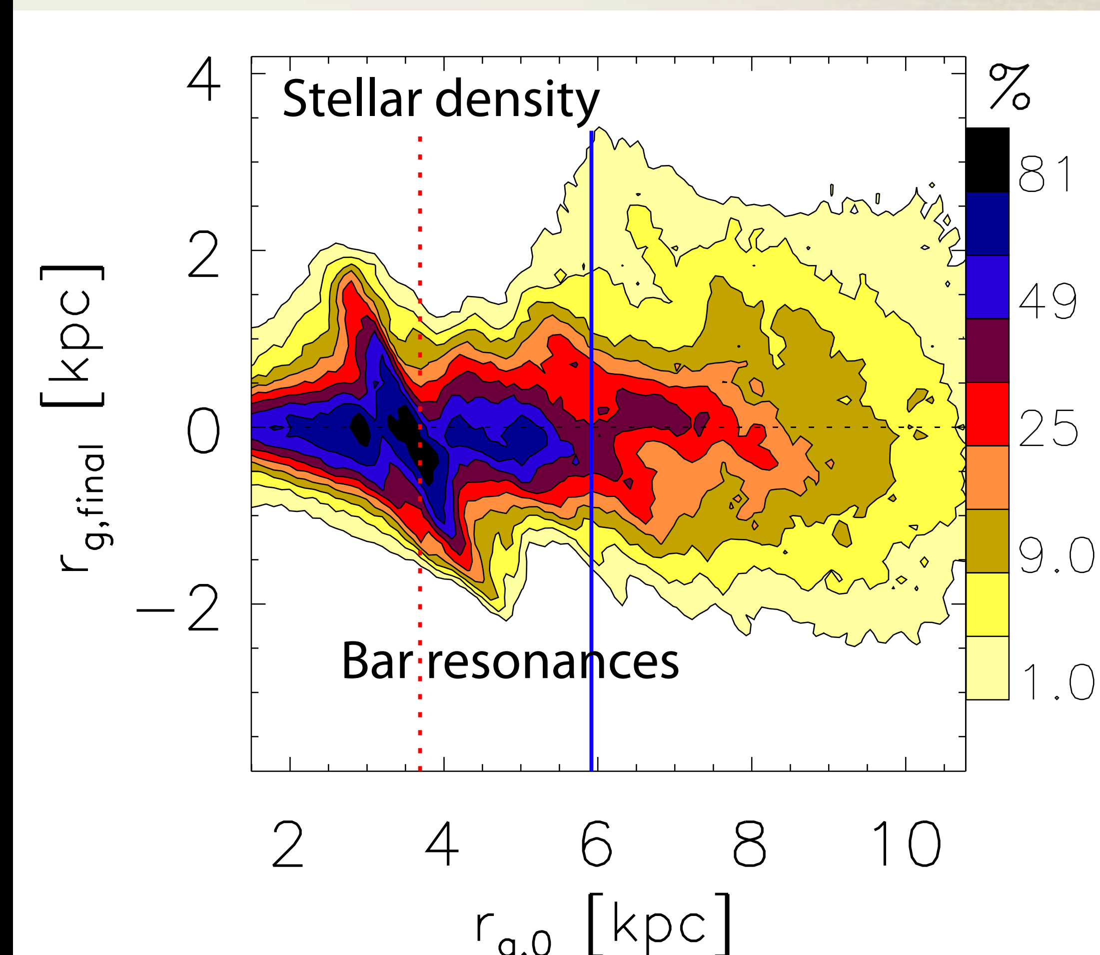




N-body Tree-SPH



Disk expands due to strong angular momentum transport outwards (Minchev et al. 2012a).

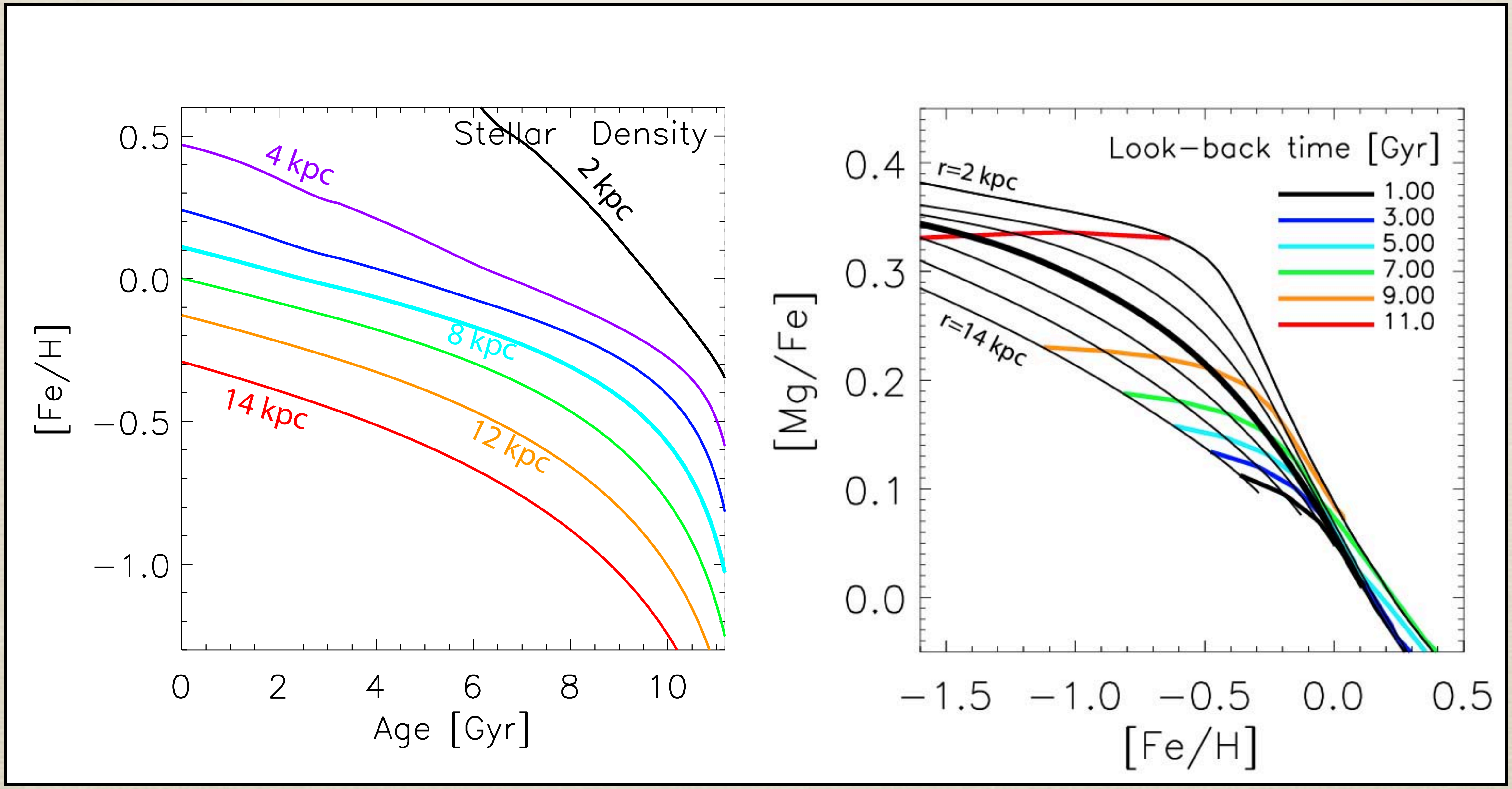


Simulations by P. Di Matteo

Chemo-dynamical evolution modeling of the Milky Way

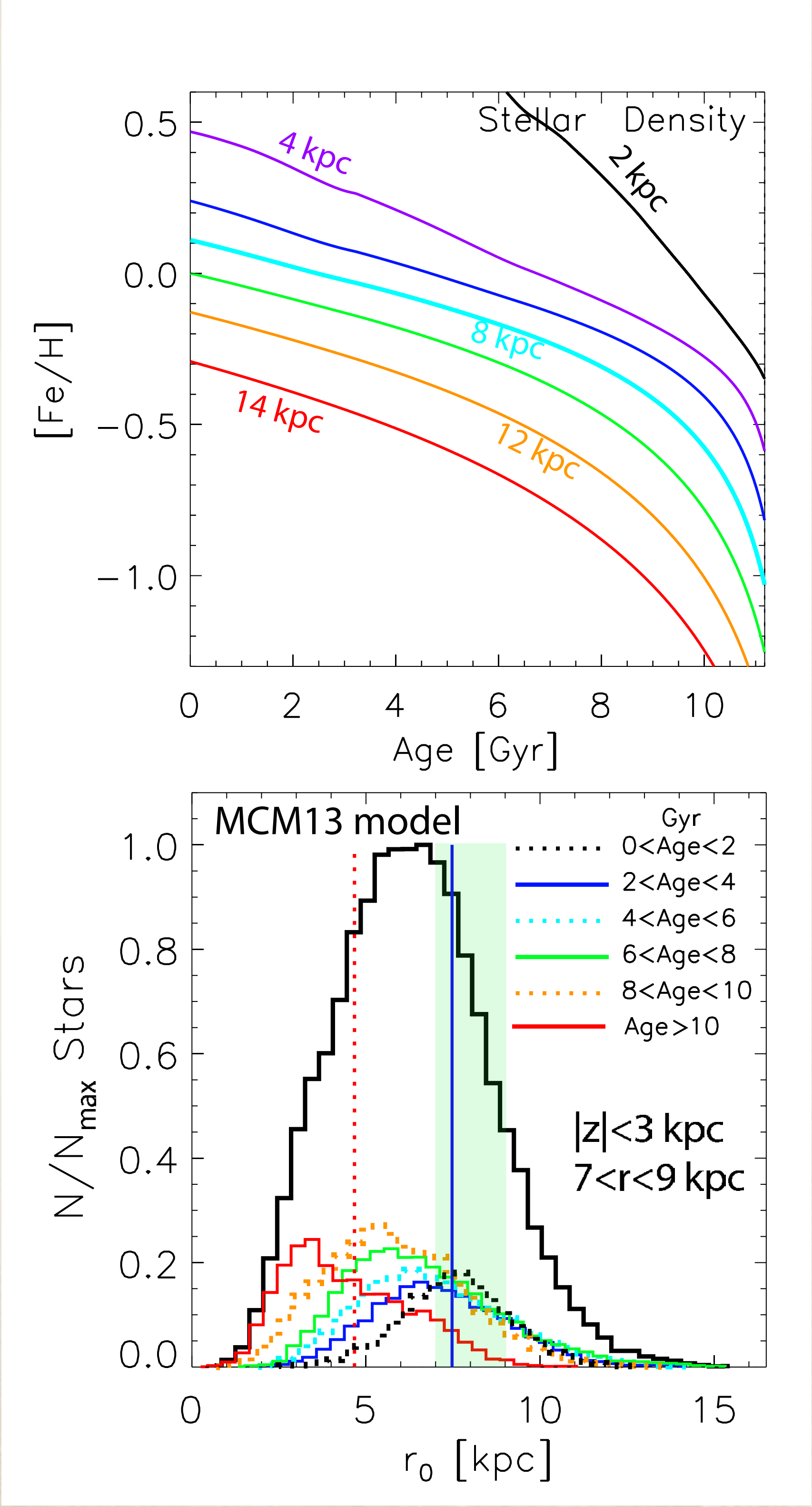
Classical chemical evolution modeling

- Classical chemical evolution models (Matteucci & Francois 1989; Prantzos & Aubert 1995; Chiappini et al. 1997, 2001).
- Stars assumed to remain close to their birth places.



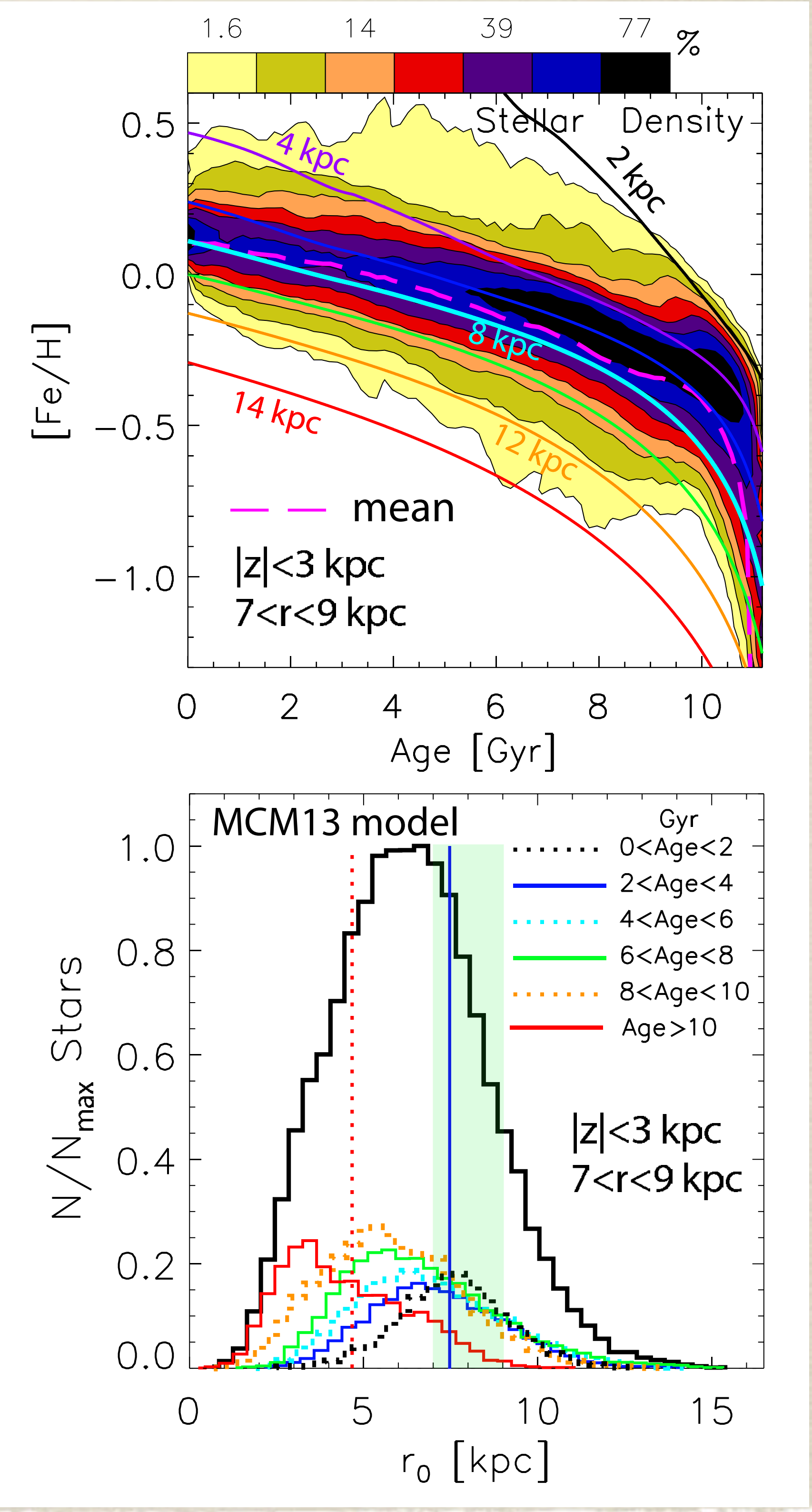
Classical chemical evolution modeling hampered by radial migration

- Stars move away from their birth places (Sellwood and Binney 2002).



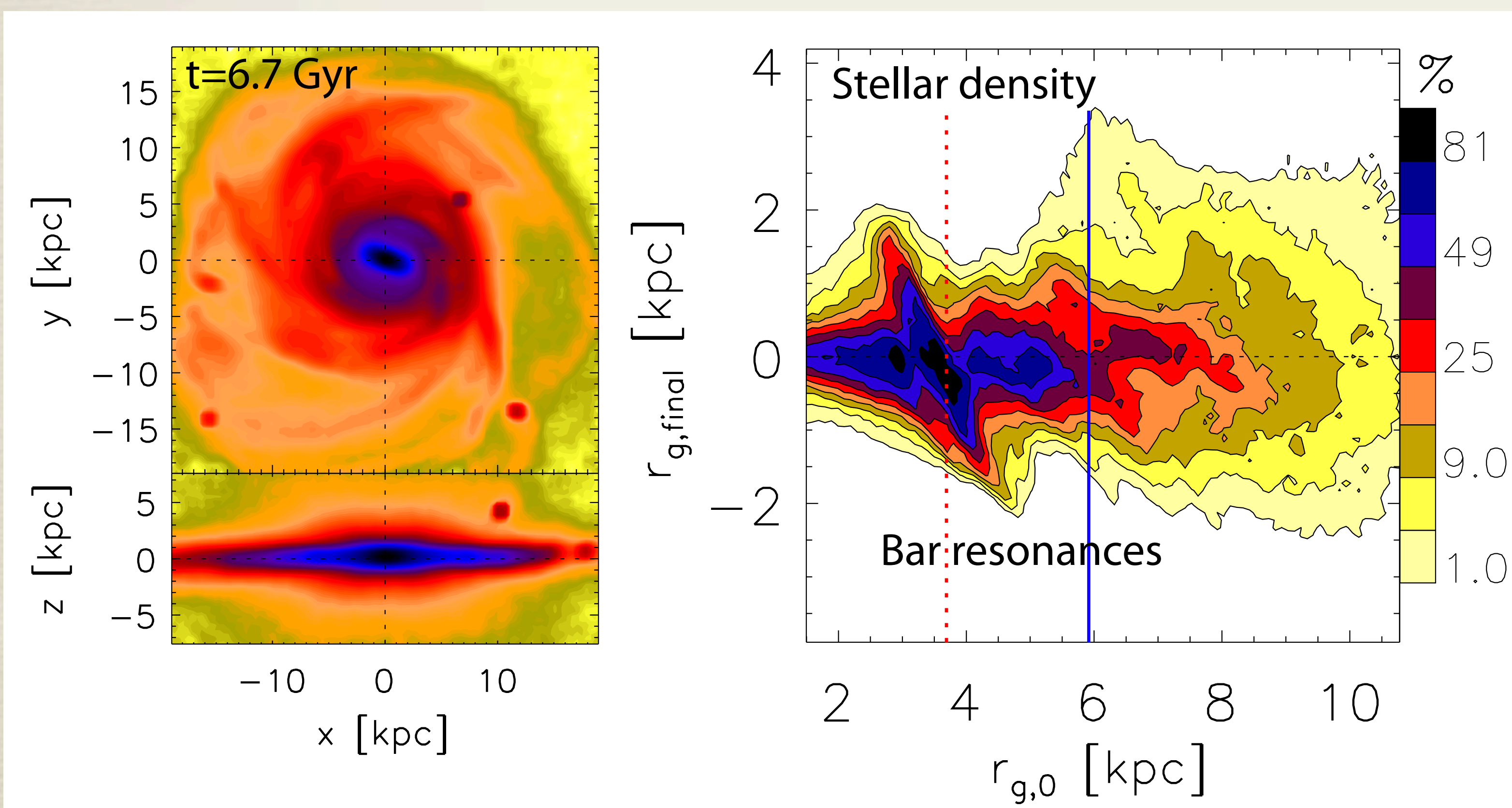
Classical chemical evolution modeling
hampered by radial migration

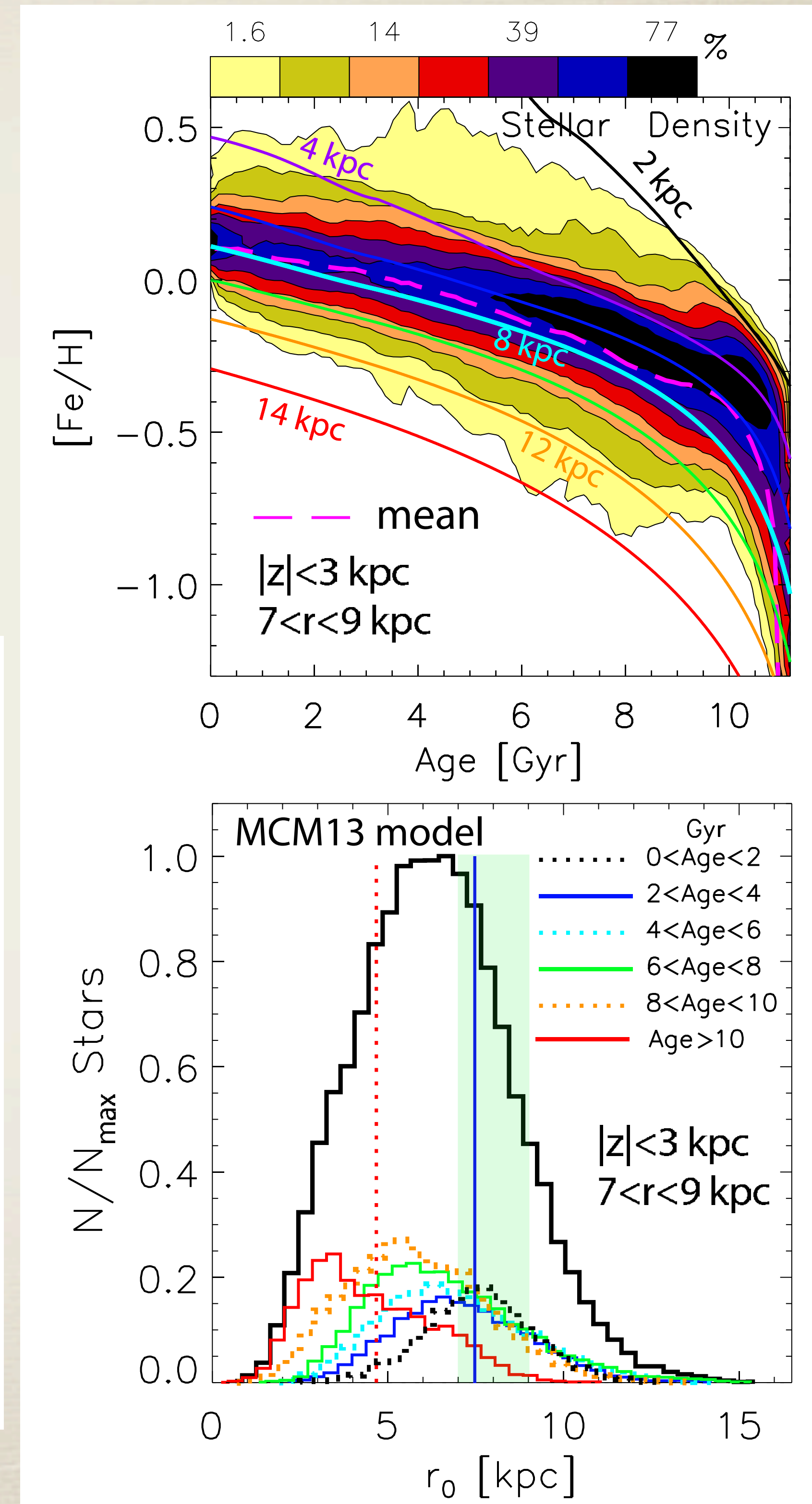
- Stars move away from their birth places (Sellwood and Binney 2002).



Classical chemical evolution modeling
hampered by radial migration

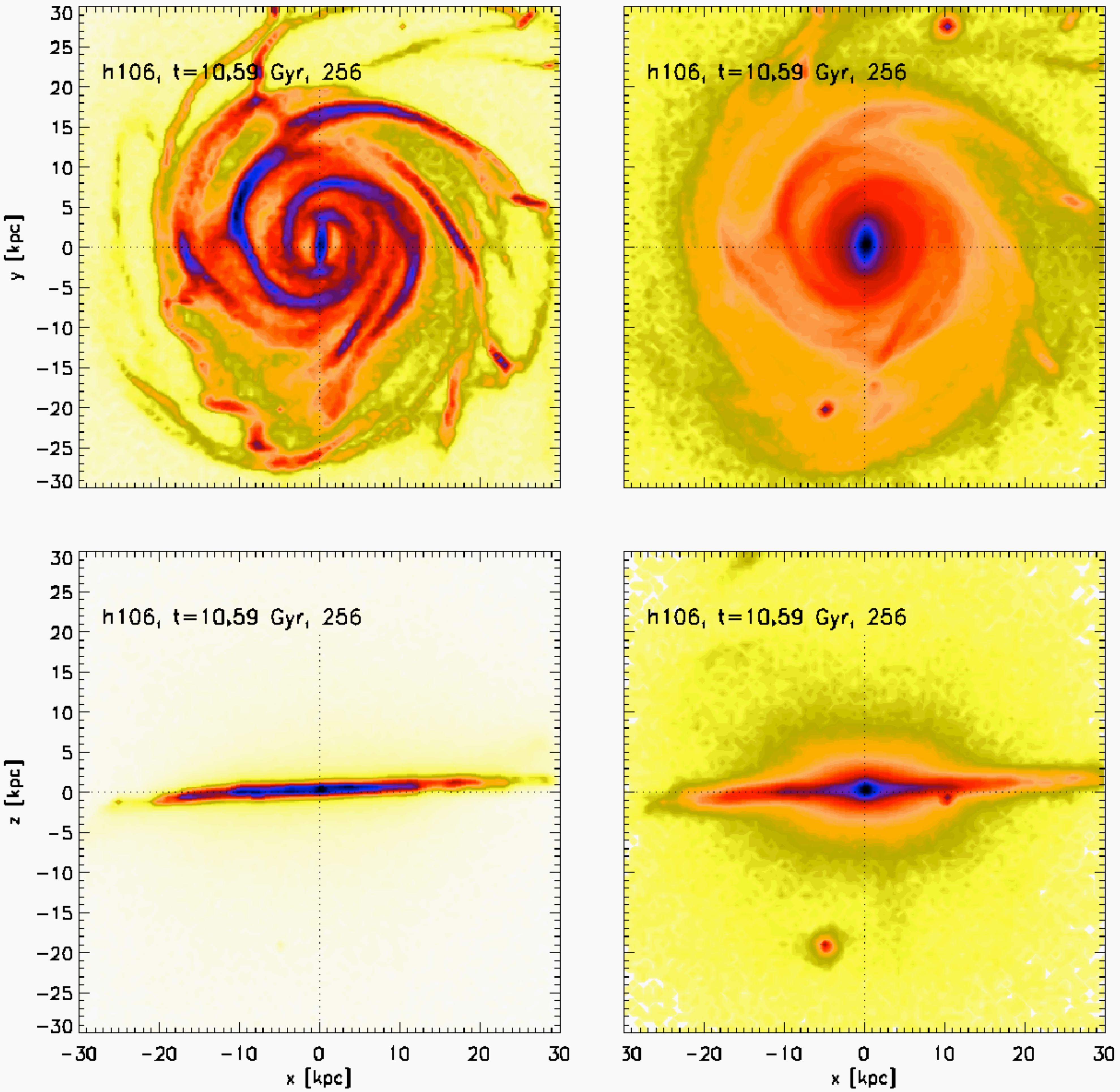
- Stars move away from their birth places (Sellwood and Binney 2002).
- We need to recover the migration efficiency as a function of Galactic radius and time.





Our chemo-dynamical model: ingredients

- A high-resolution simulation of a disk assembly in the cosmological context:
  - Gas infall form filaments and gas-rich mergers
  - Merger activity decreasing toward redshift zero
- Disk properties at redshift zero consistent with the dynamics and morphology of the Milky Way:
  - The presence of a Milky Way-size bar
  - A small bulge
  - Bar's Outer Lindblad Resonance at ~2.5 disk scale-lengths
- A detailed chemical evolution model:
  - Matching several observational constraints in the Milky Way.



Simulation in cosmological context

Martig et al. (2009, 2012)

Stars born hot at high redshift:

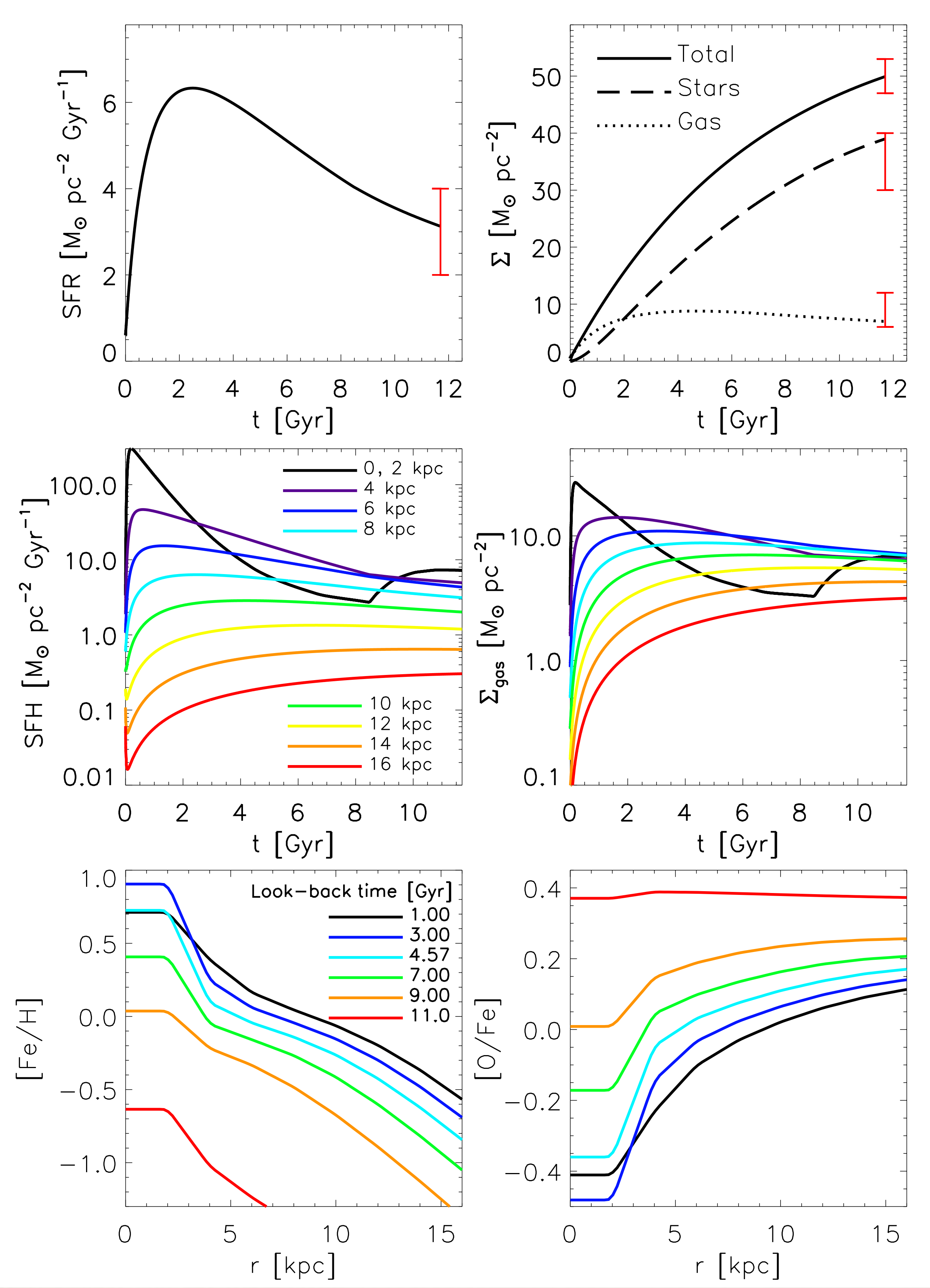
Similar to

Brook et al. (2012),

Stinson et al. (2013),

Bird et al. (2013)

Chemical model



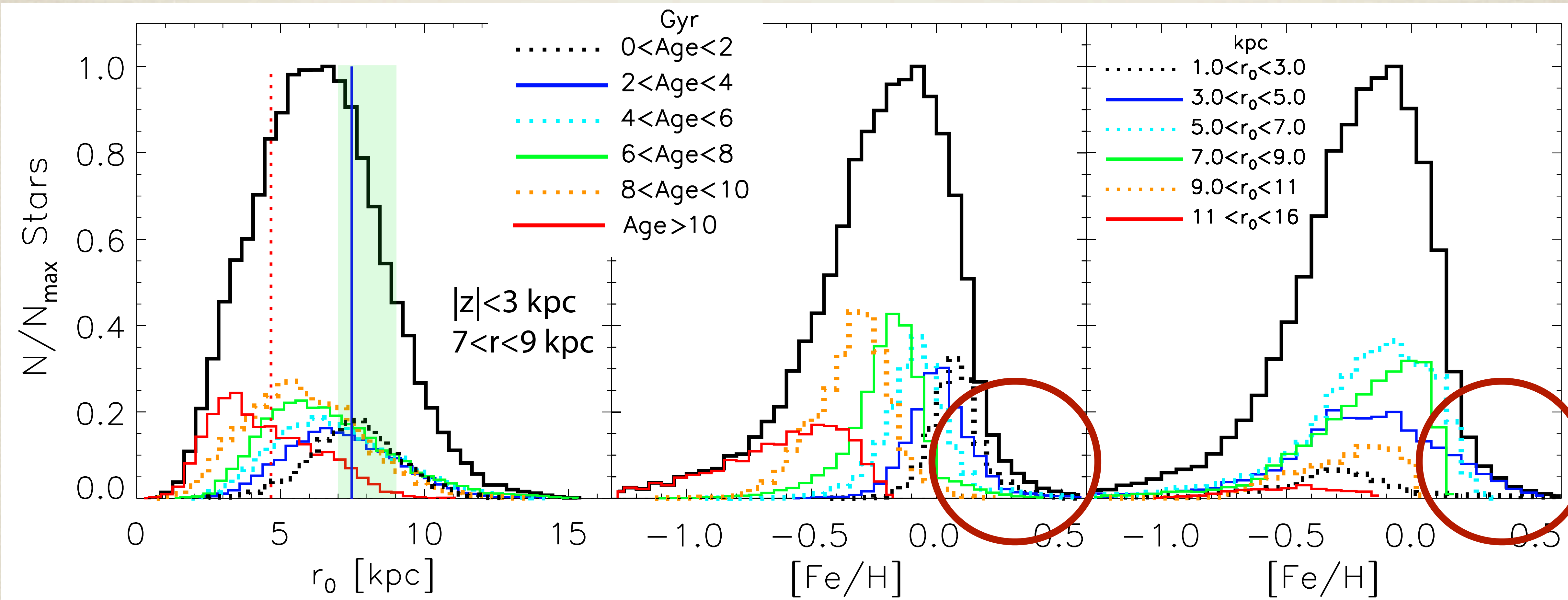
Similar to Chiappini (2009)

Constrained by:

- The solar and present day abundances of more than 30 elements
- The present SFR
- The current stellar, gas and total mass densities at the solar vicinity
- The present day supernovae rates of type II and Ia
- The metallicity distribution of G-dwarf stars

- Only thin disk chemistry used!

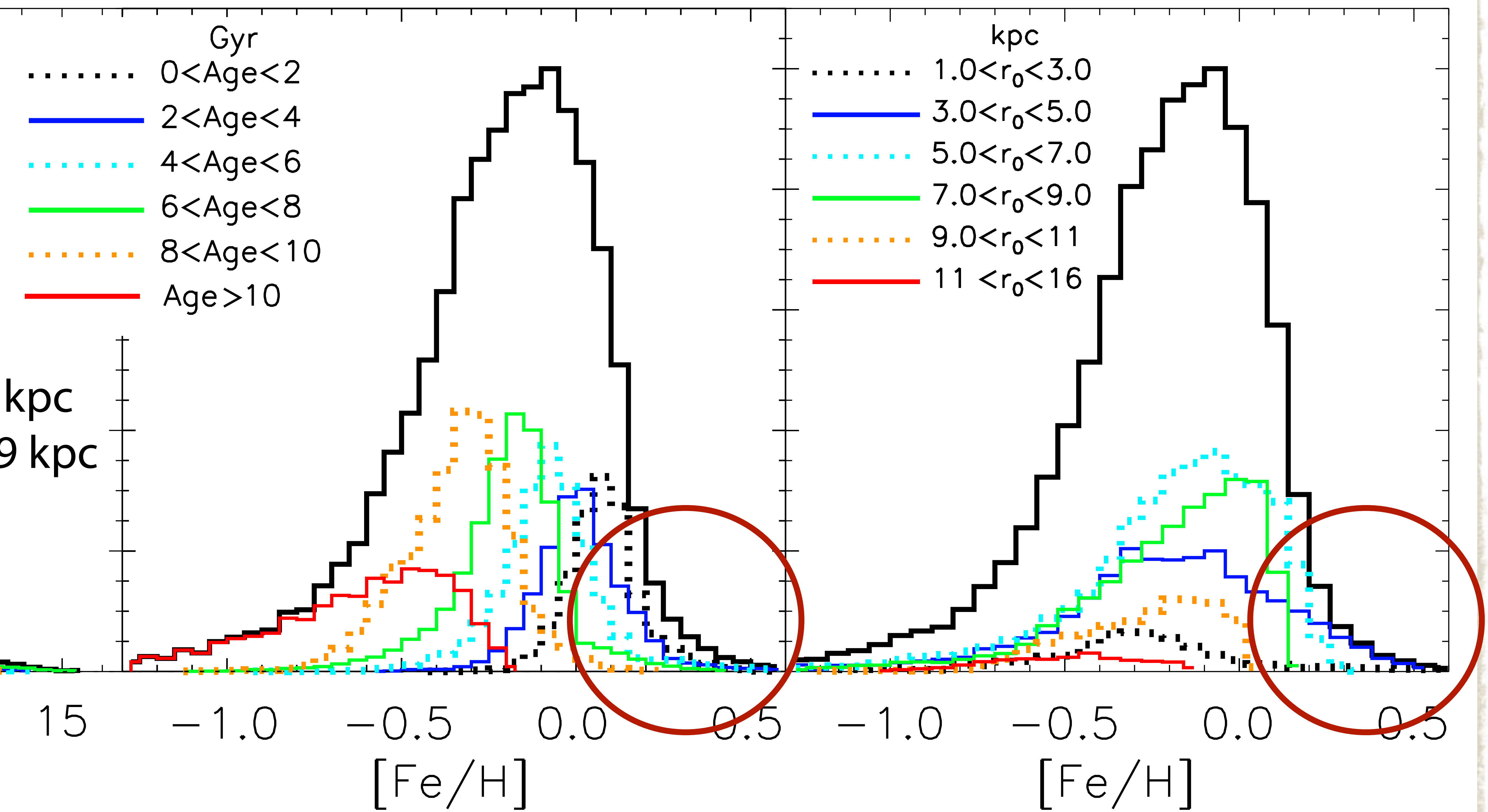
Origin and metallicity distributions of local stars



Minchev, Chiappini & Martig (2013)

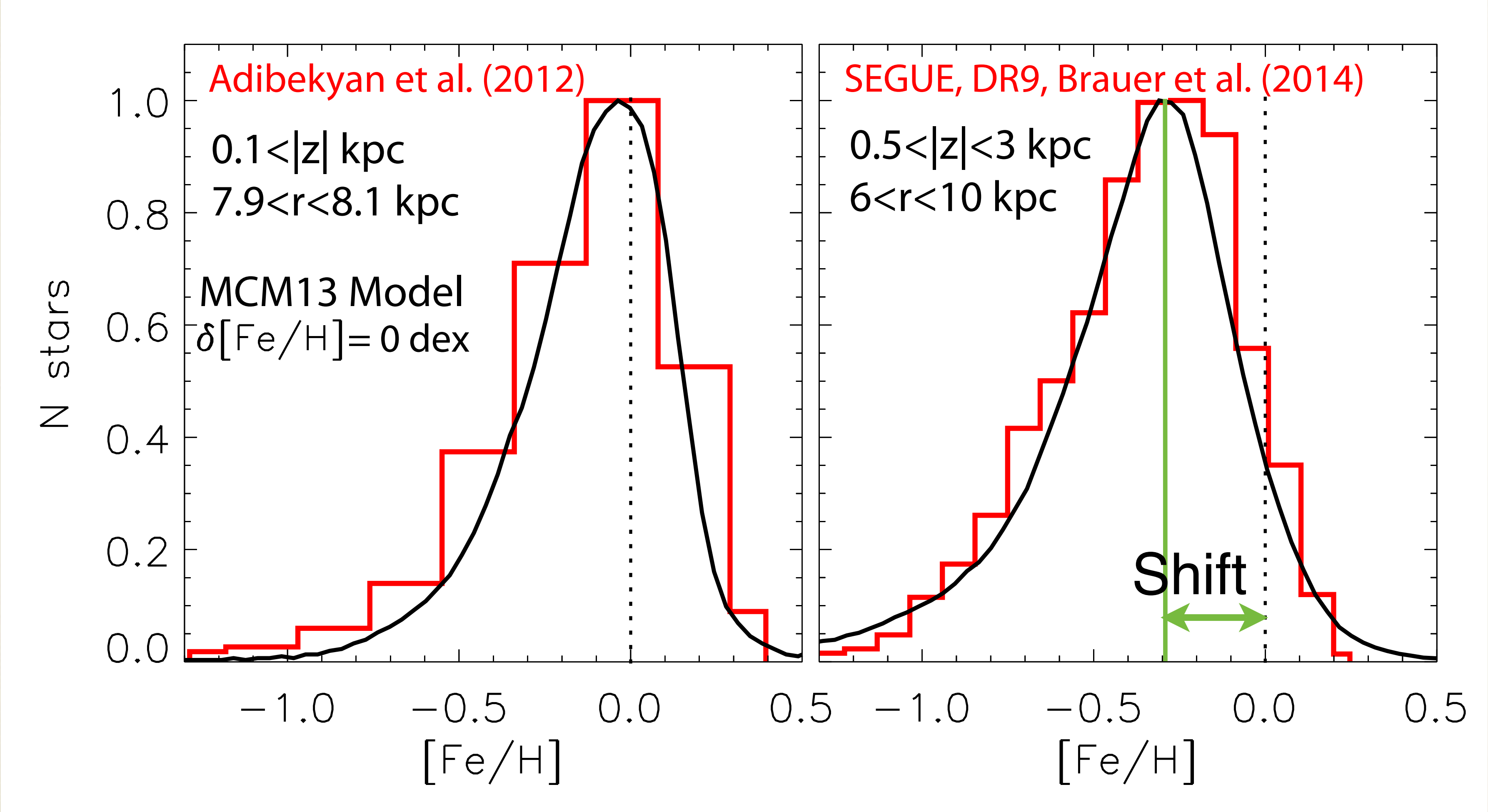
Older populations arrive from progressively smaller galactic radii due to their longer exposure to migration.

Origin and metallicity distributions of local stars



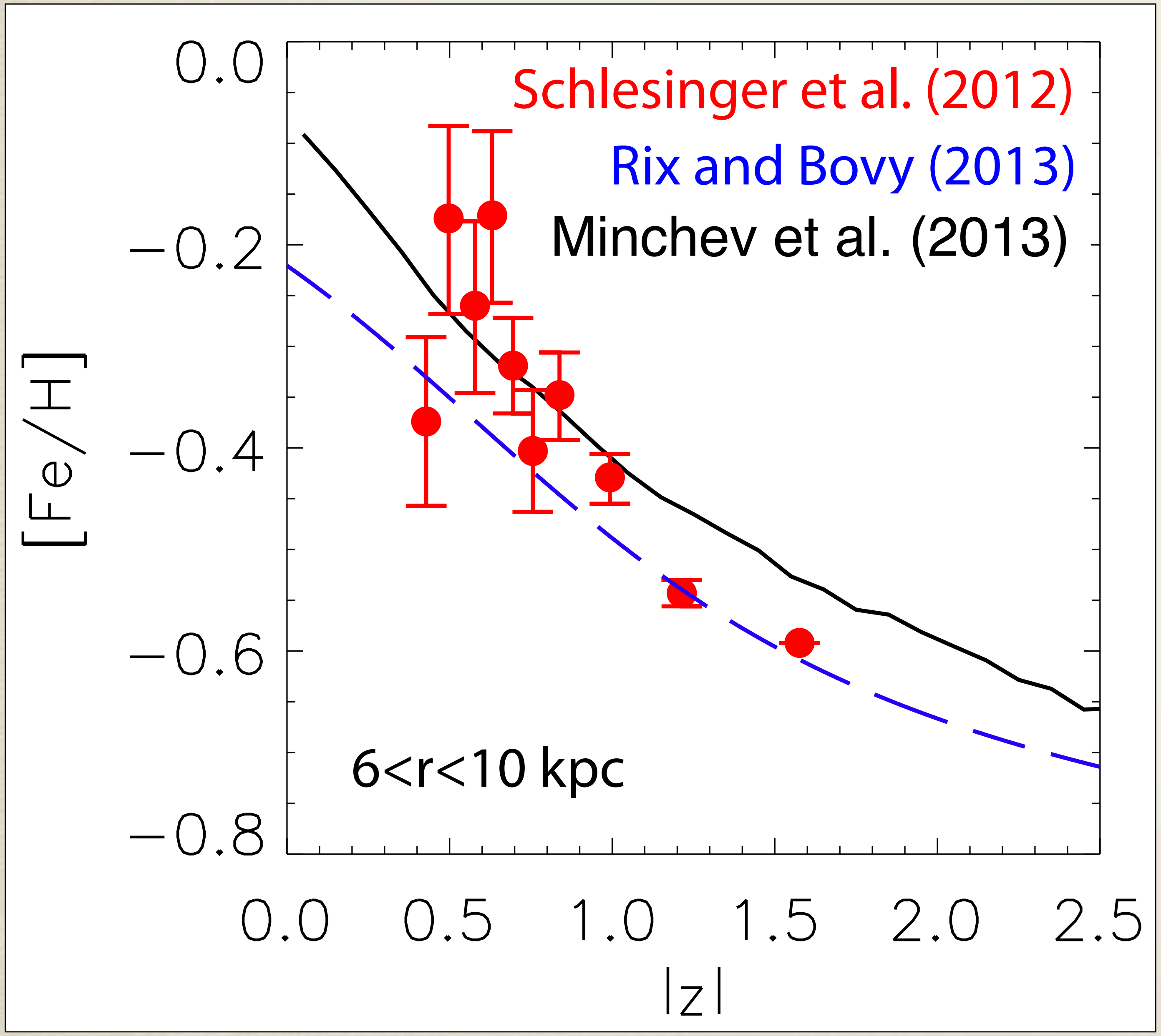
The metallicity distribution

|z| < 40 pc　　　　|z| > 500 pc



For both model and observations the MDF peak shifts to lower [Fe/H] with distance from the disk plane

The vertical metallicity gradient



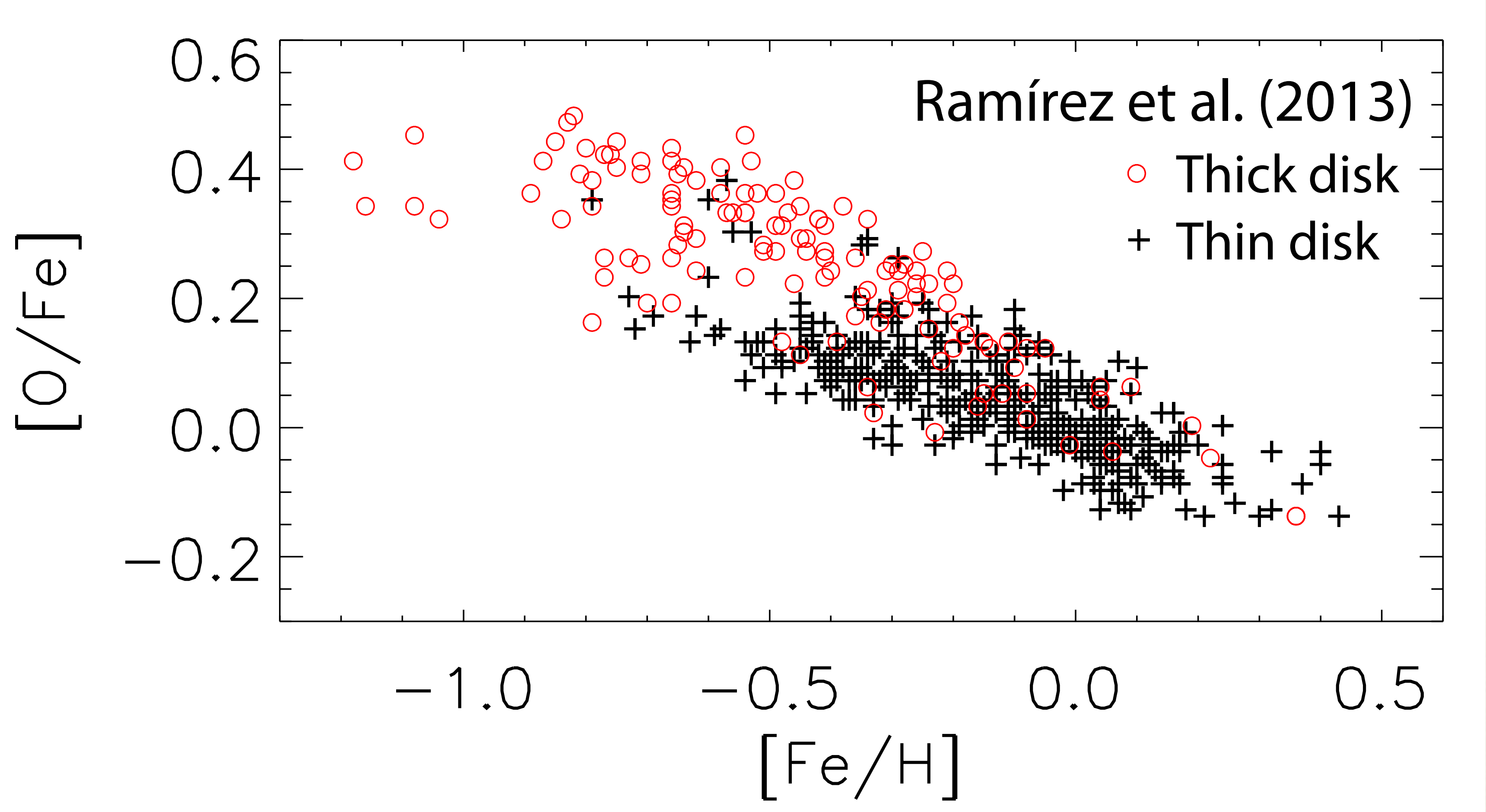
Schlesinger et al. (2012), G-dwarfs

Bovy model, Rix & Bovy (2013)

Minchev et al. (2013)

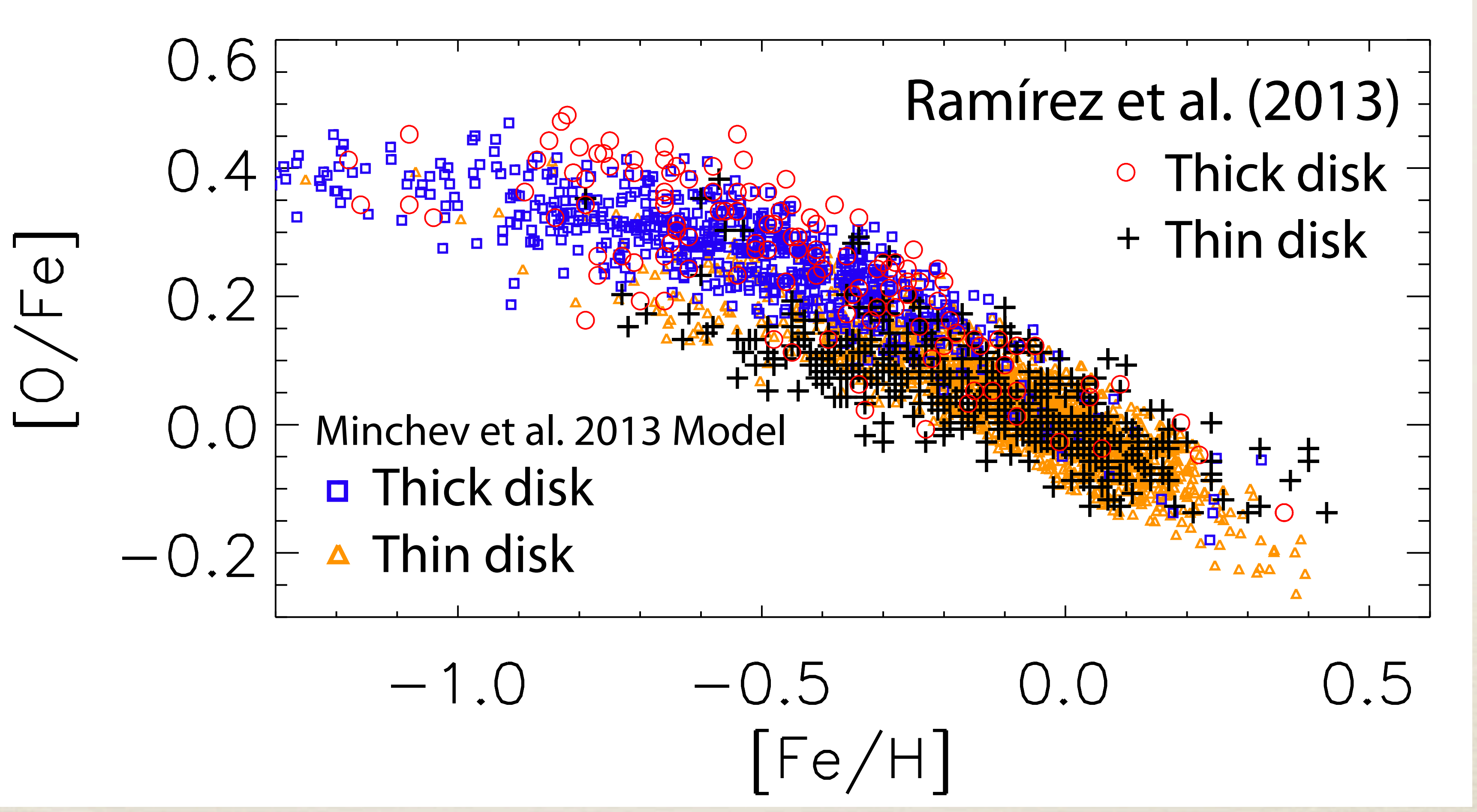
The [Fe/H]-[O/Fe] relation

Kinematical selection of thin- and thick-disk populations

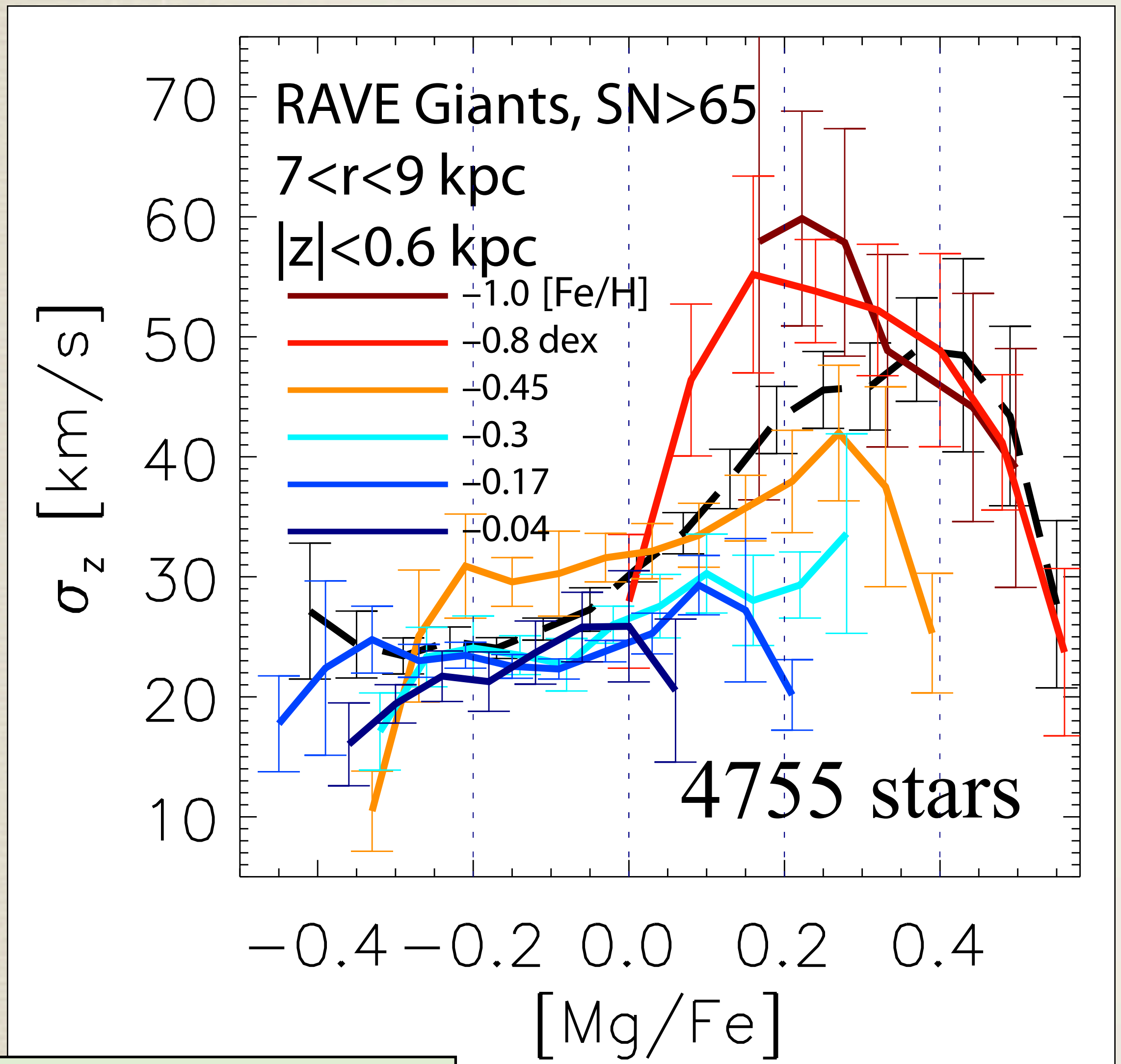


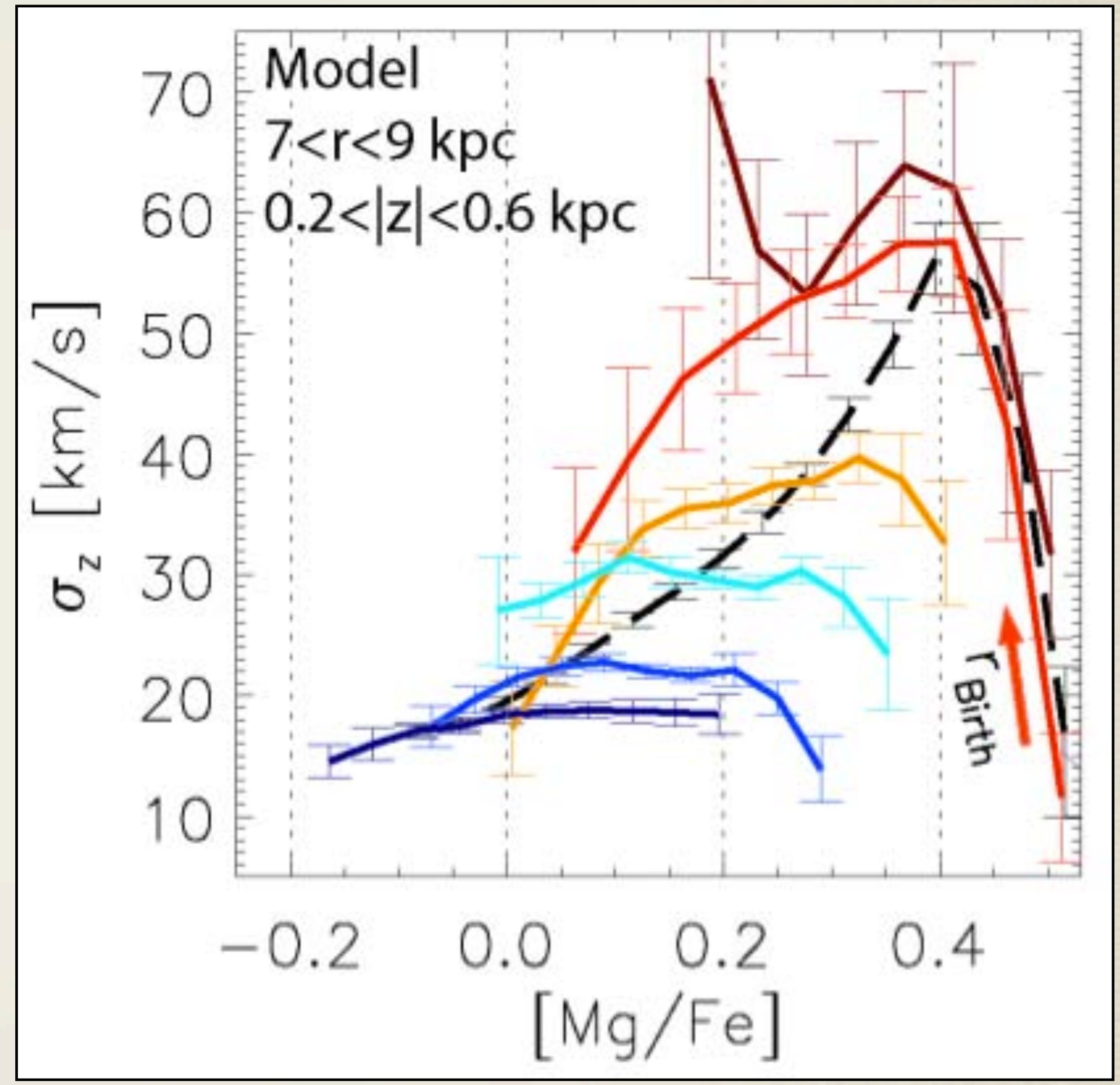
The [Fe/H]-[O/Fe] relation

Kinematical selection of thin- and thick-disk populations



Variation of velocity dispersion with [Mg/Fe]

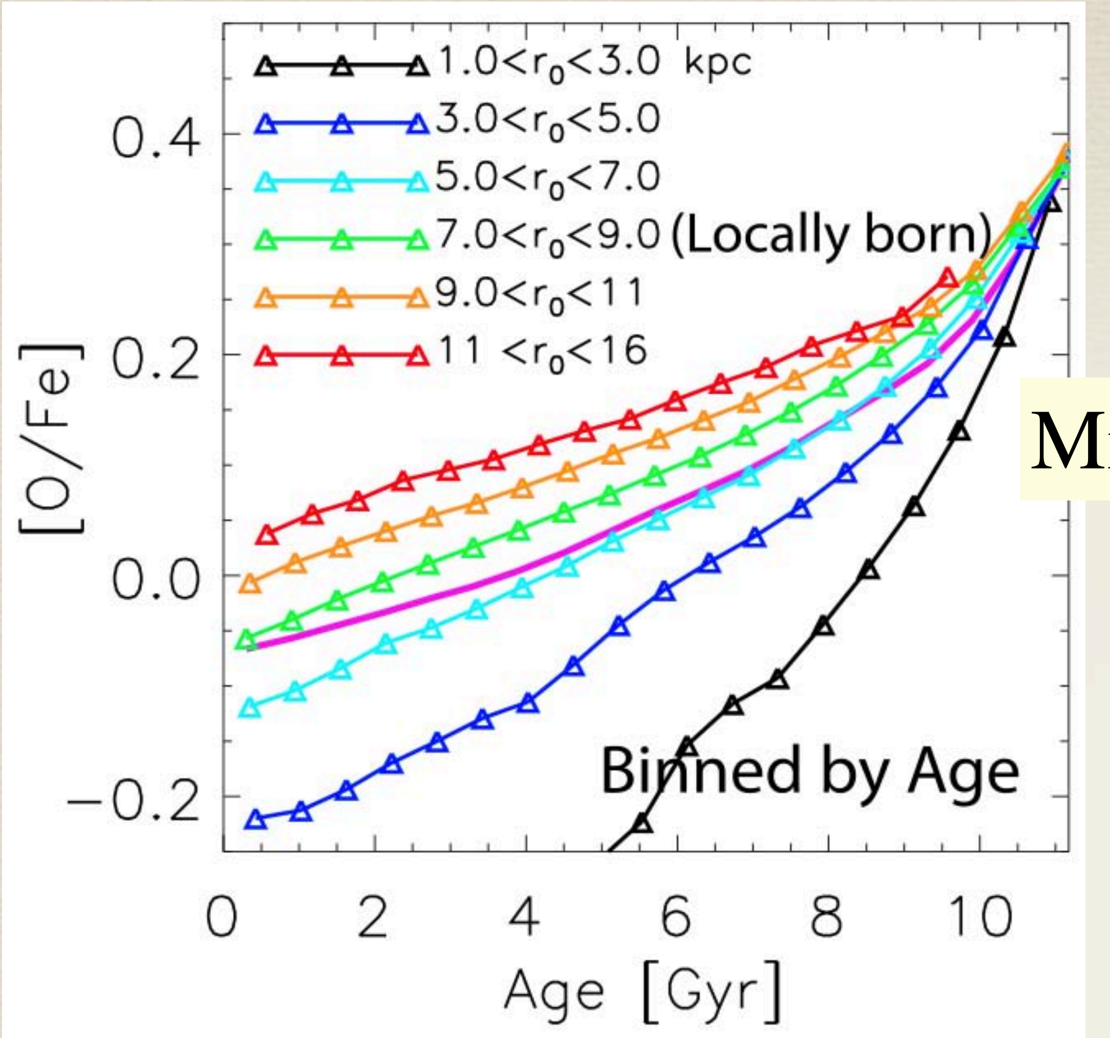




Minchev + RAVE (2014)

Velocity dispersion drops at the high-[Mg/Fe] end for each metallicity sub-population

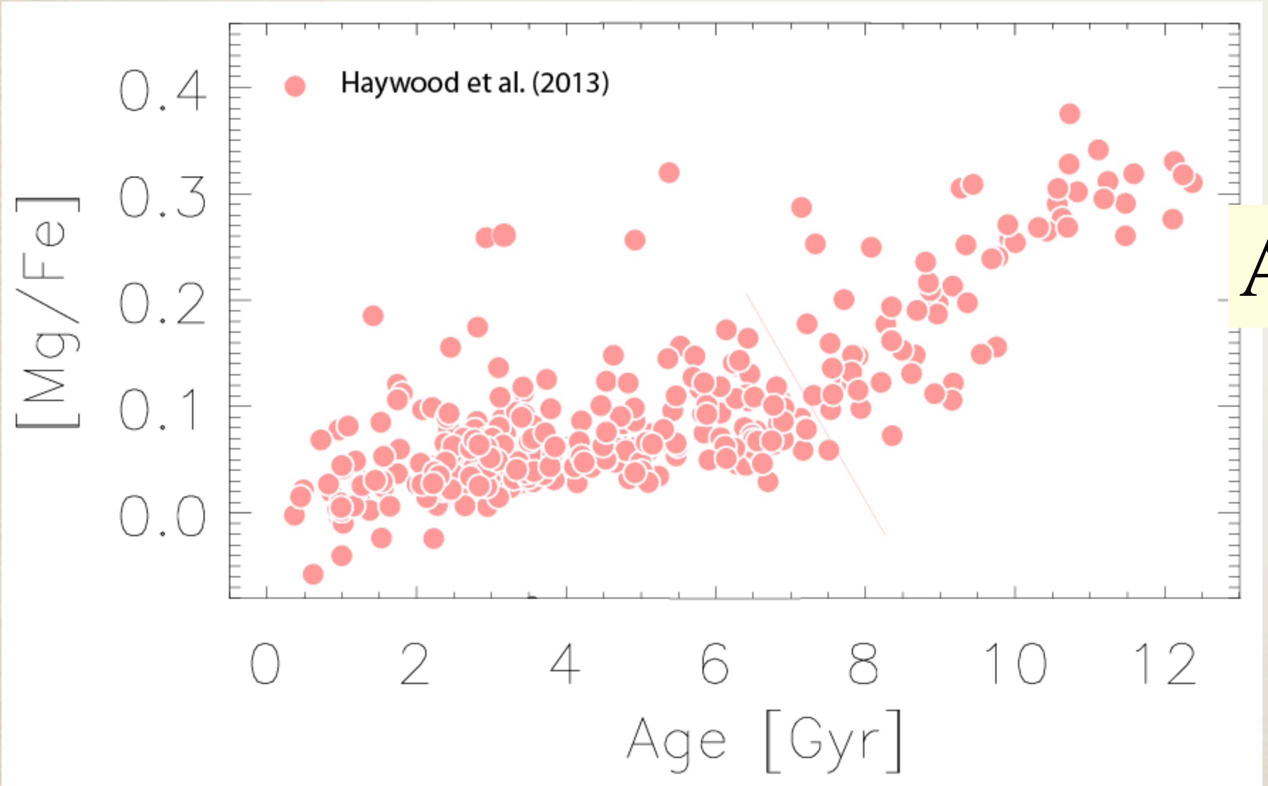
The age-[α/Fe] relation



Minchev et al. (2013) model

Density not shown in this figure!

Density strongly declines away from the mean as most stars born close to the solar radius.

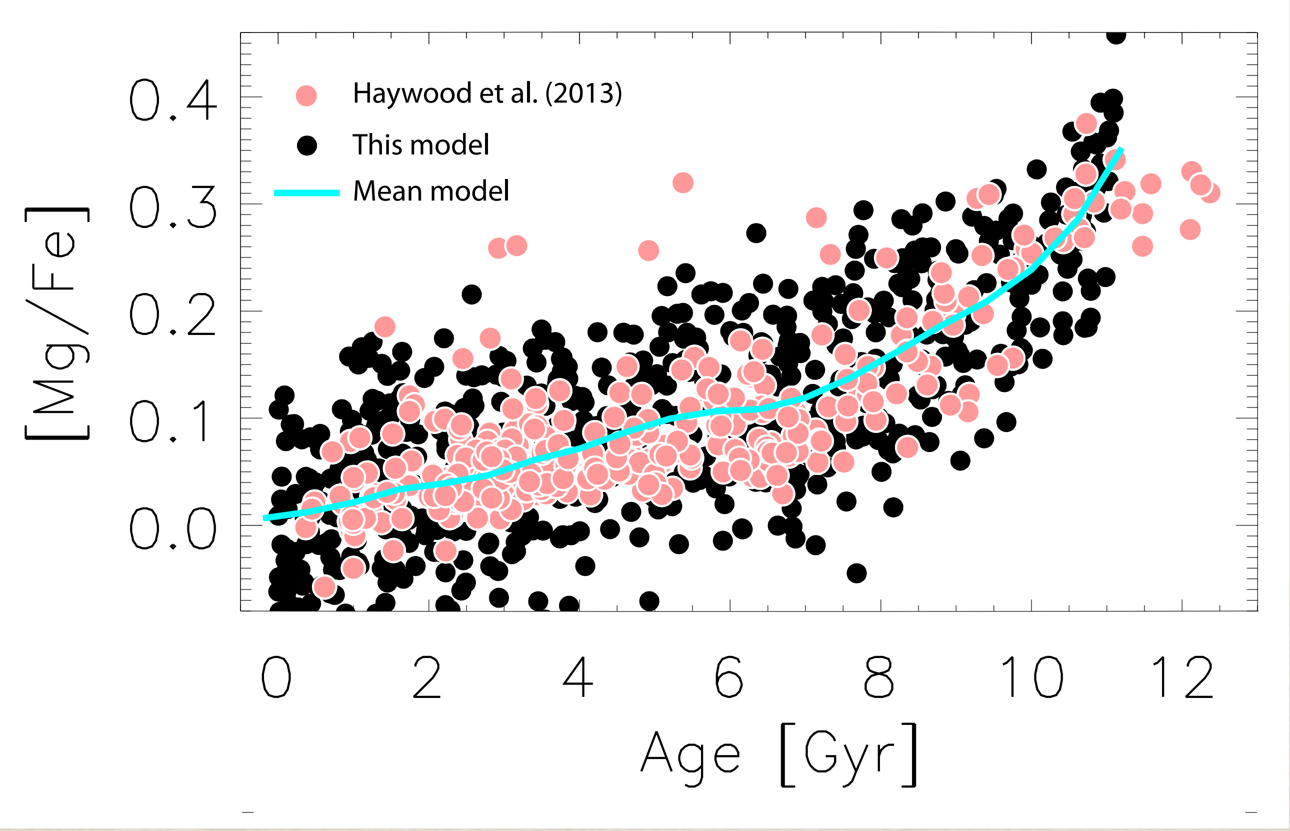


Adibekyan + Haywood sample

A density plot.

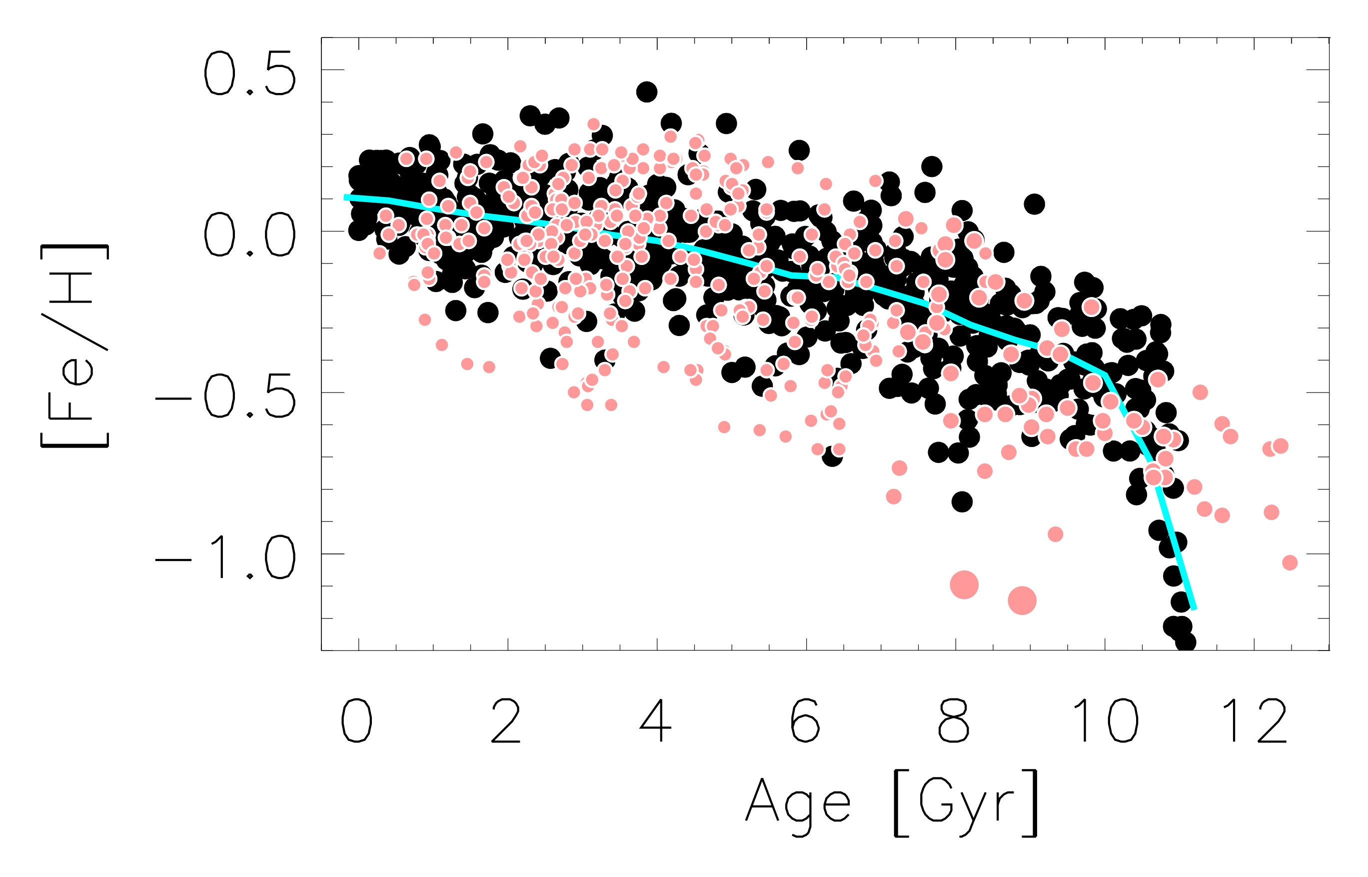
The age-[α/Fe] and age-[Fe/H] relations

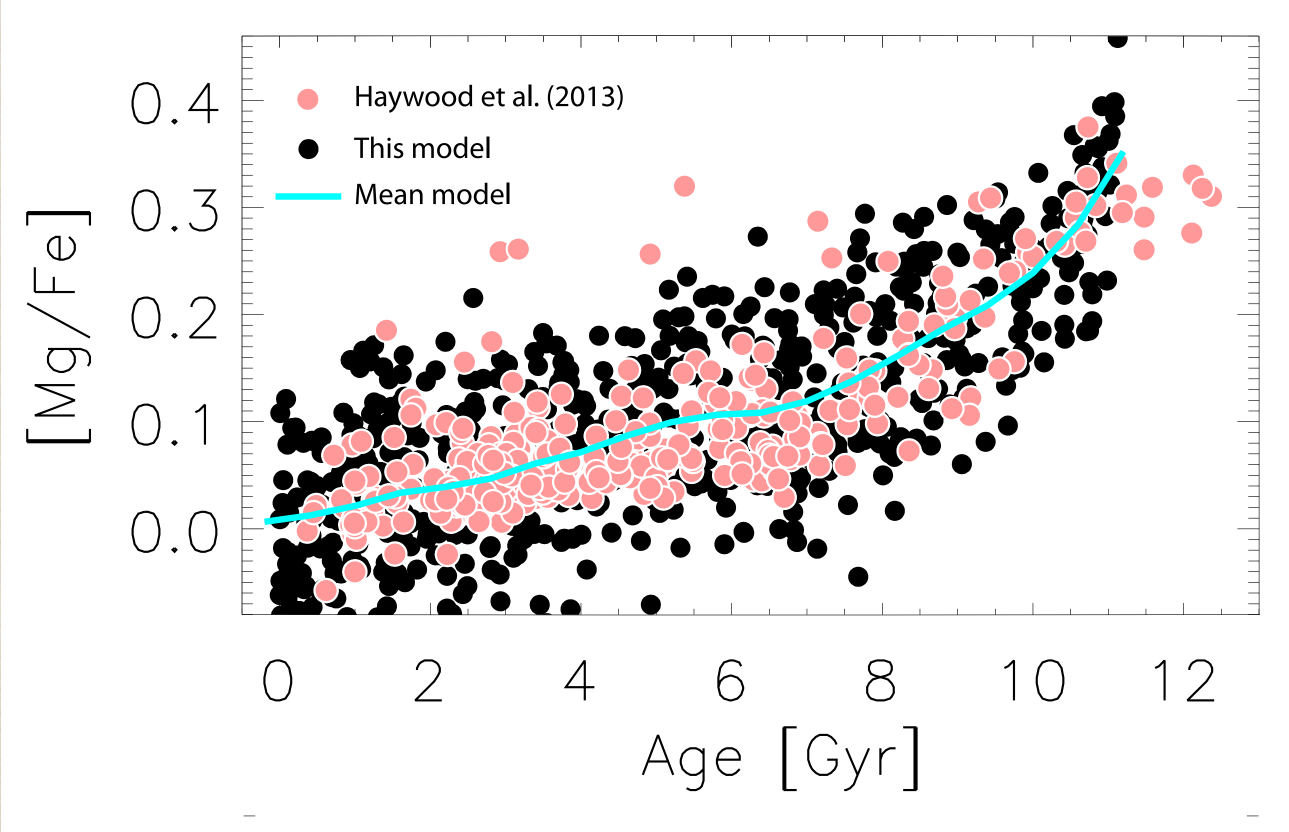
Comparison between our model and the Adibekyan + Haywood sample



The age-[α/Fe] and age-[Fe/H] relations

Comparison between our model and the Adibekyan + Haywood sample





The age-[α/Fe] and age-[Fe/H] relations

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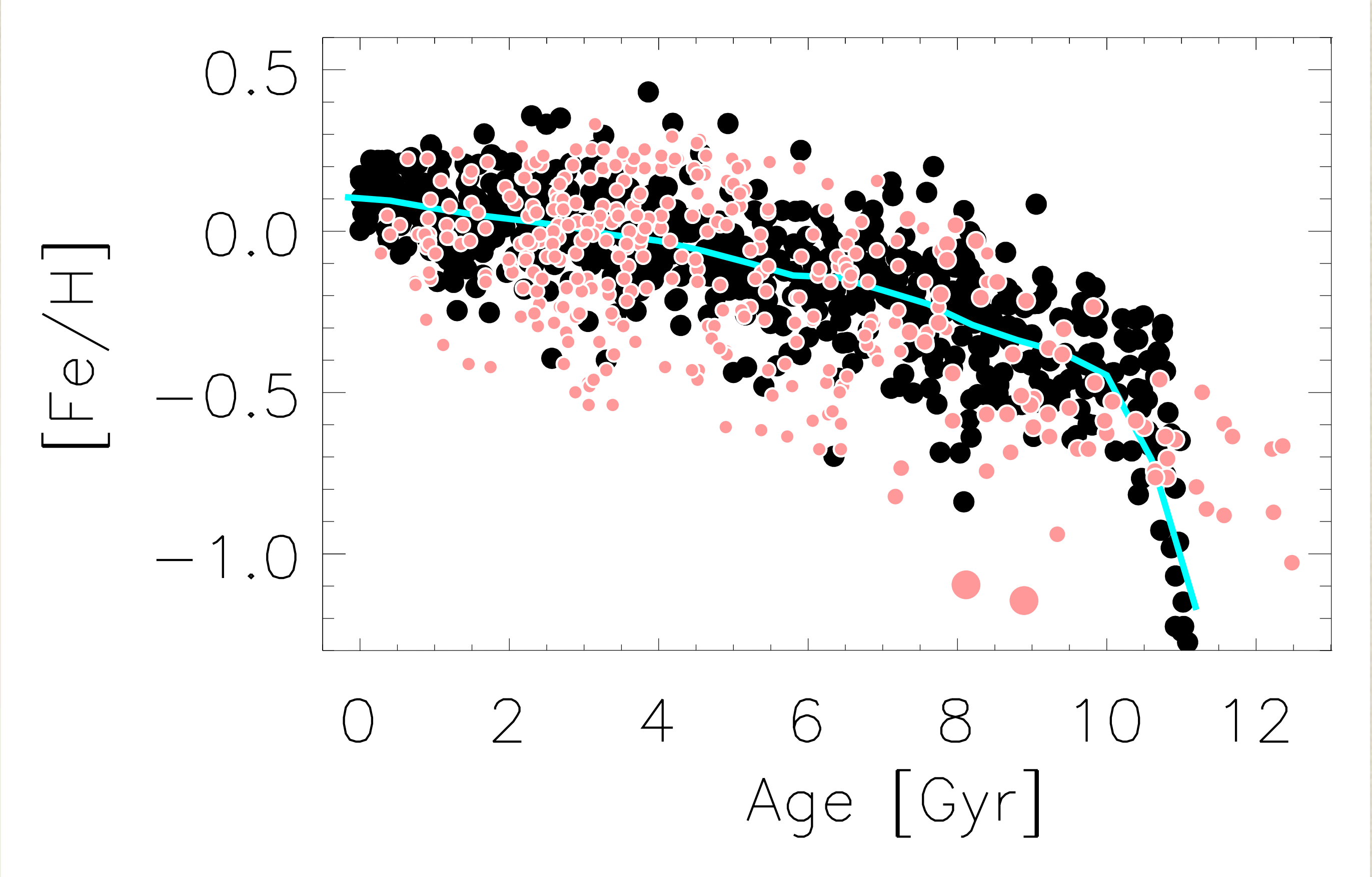
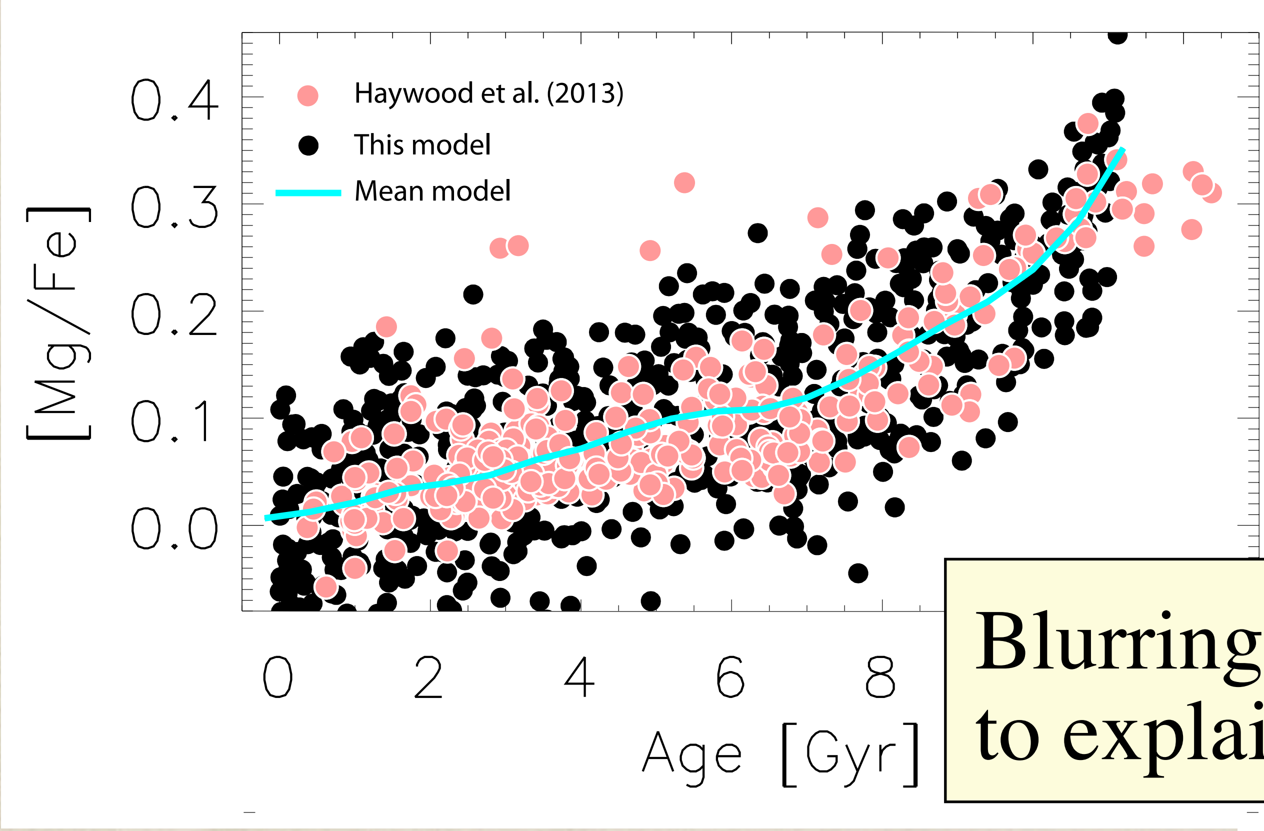
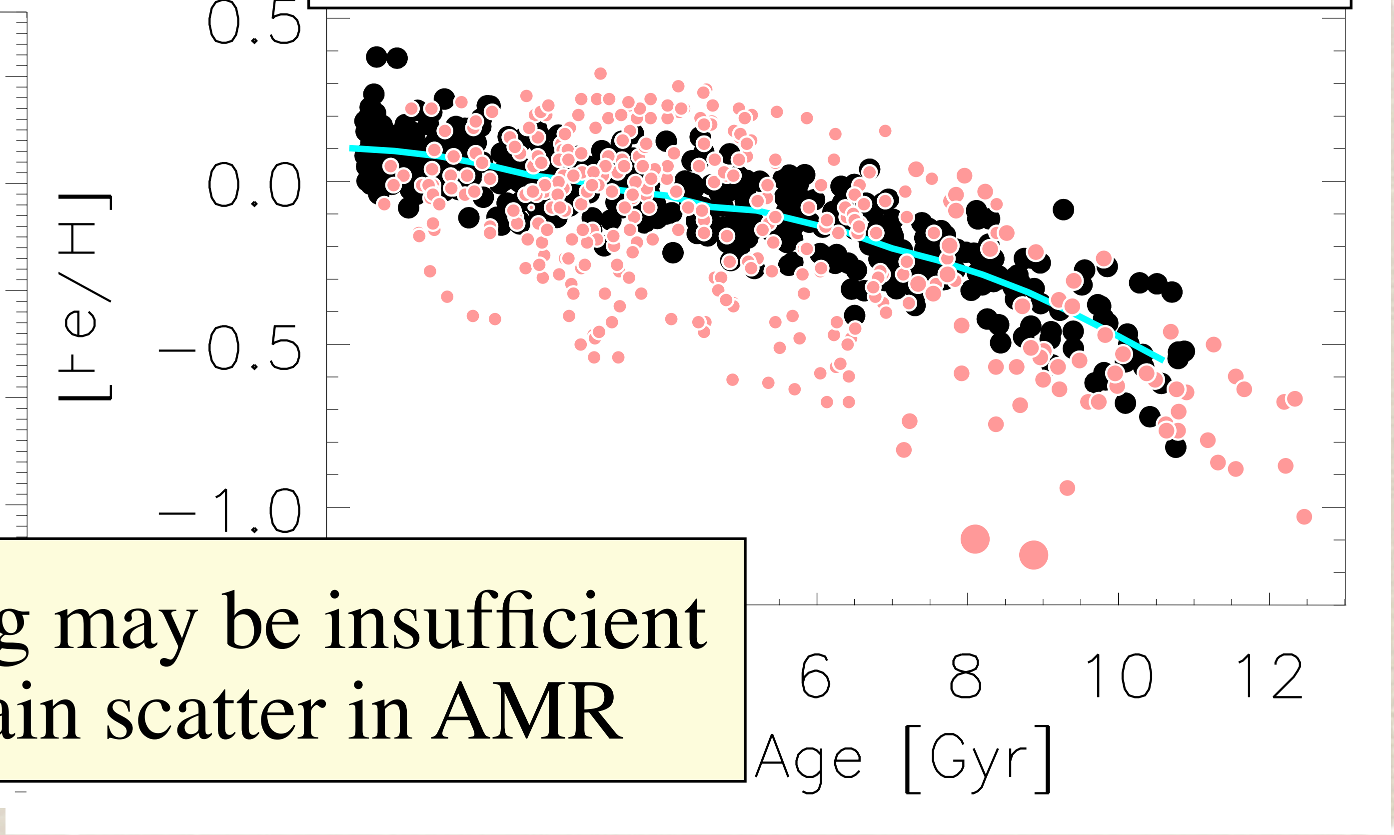
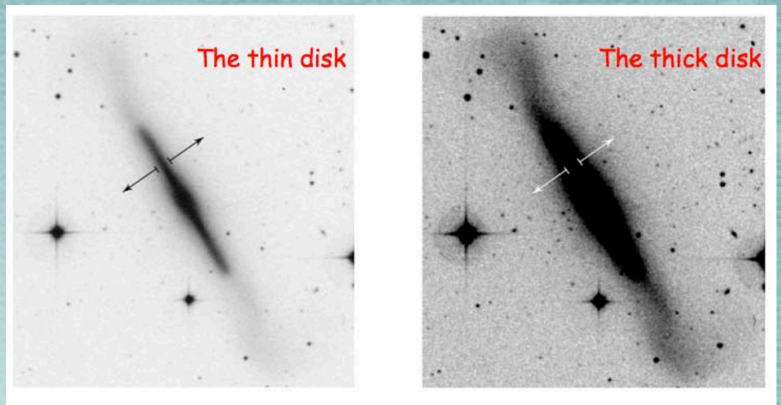




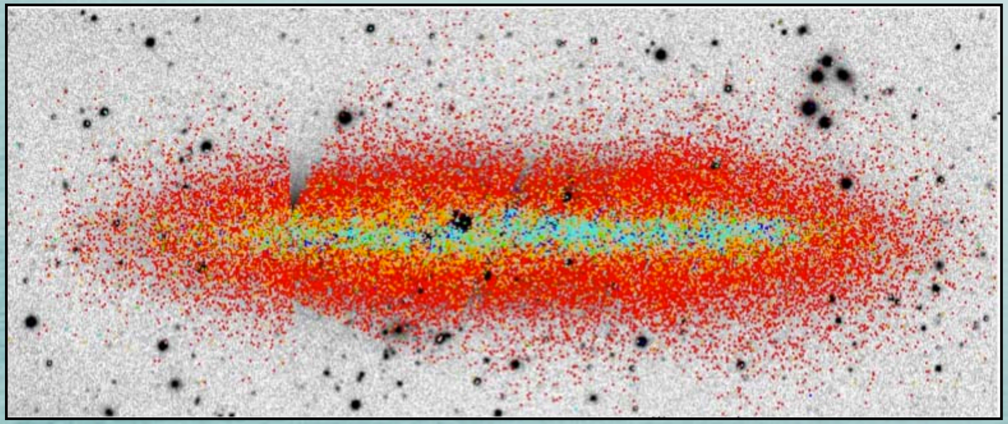
Migrators removed in model



Blurring may be insufficient to explain scatter in AMR

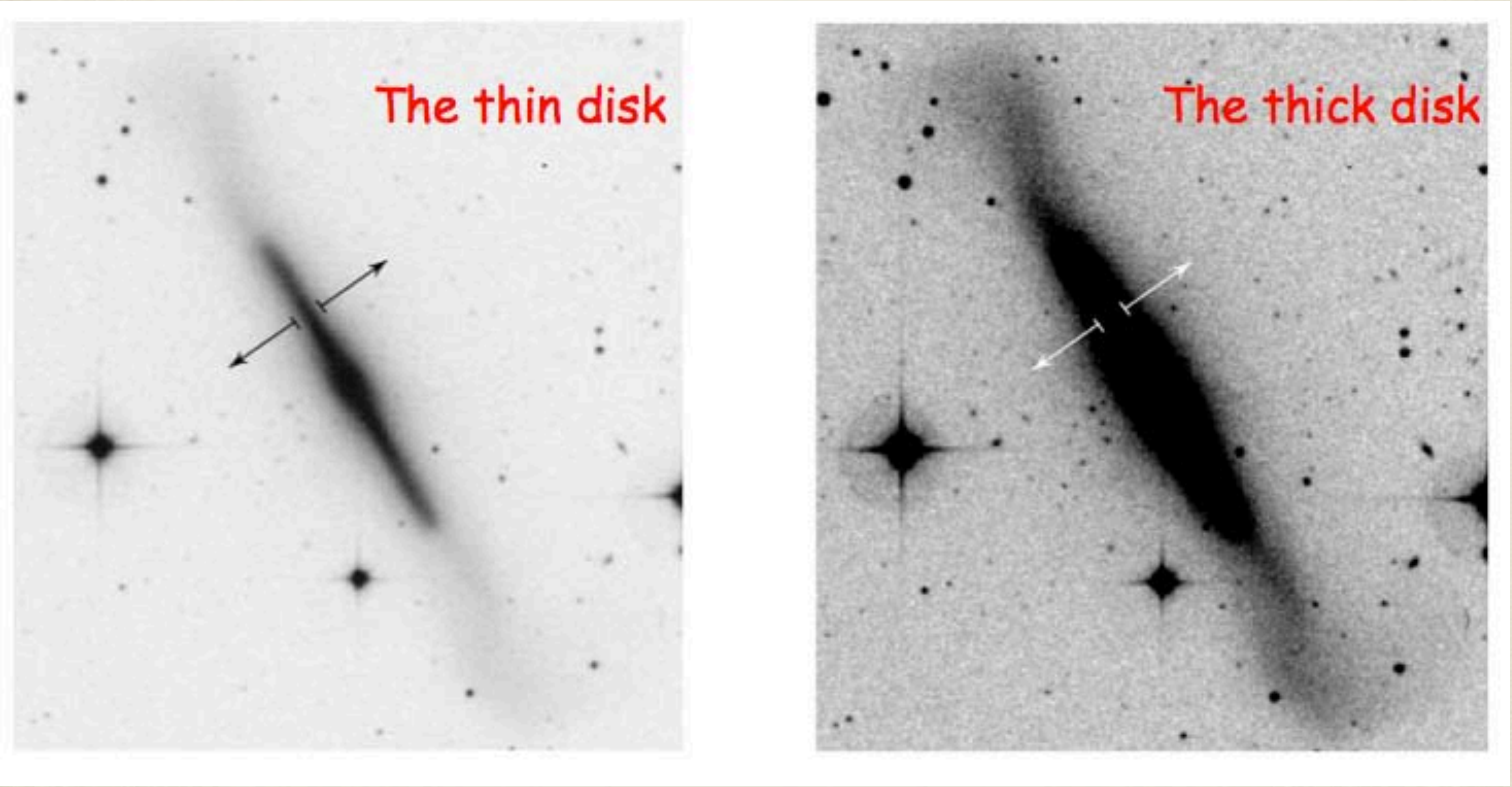


On the formation of galactic thick disks



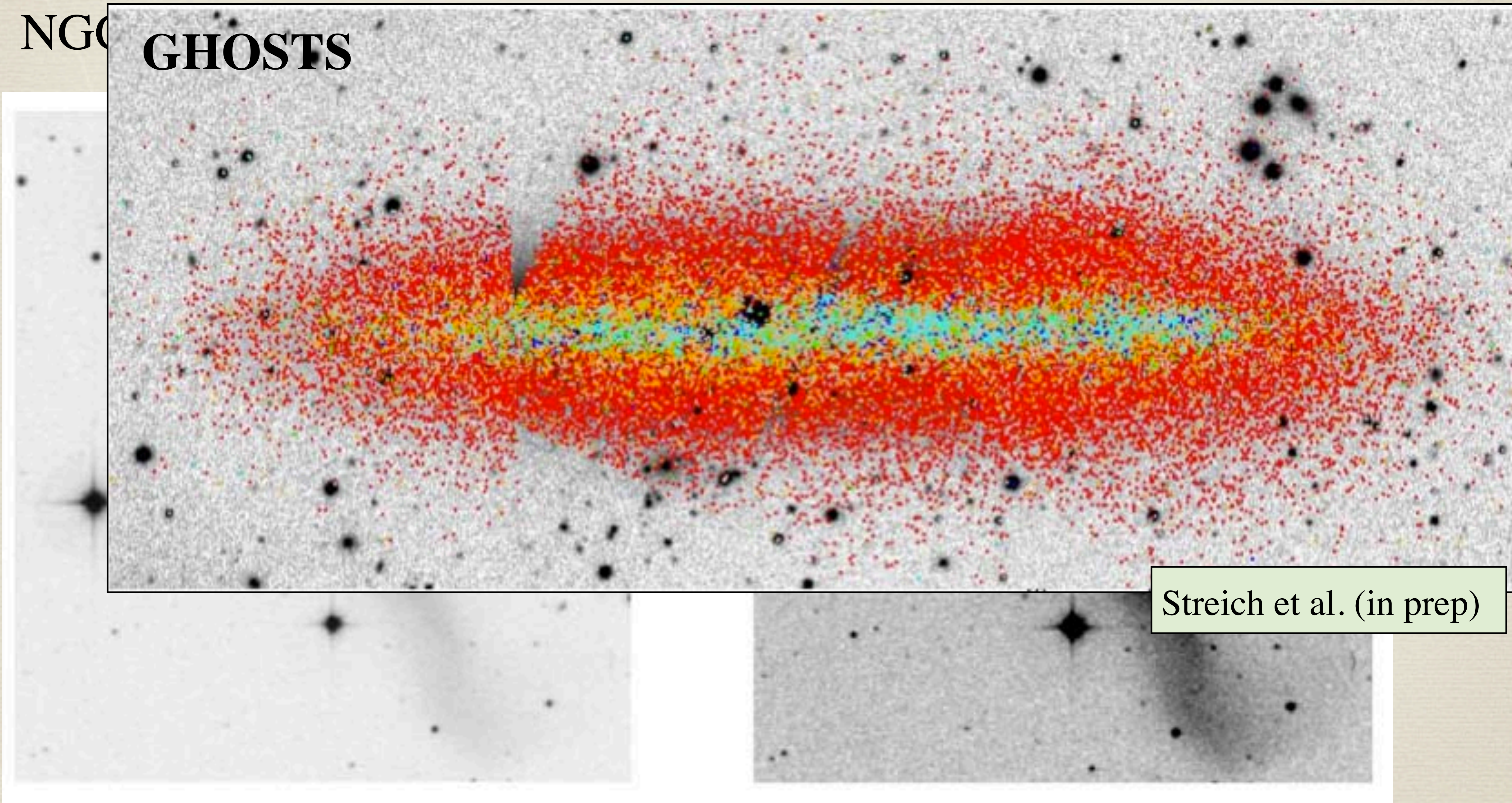
Thick disks are **extended**

NGC 4762 - a disk galaxy with a bright thick disk (Tsikoudi 1980)



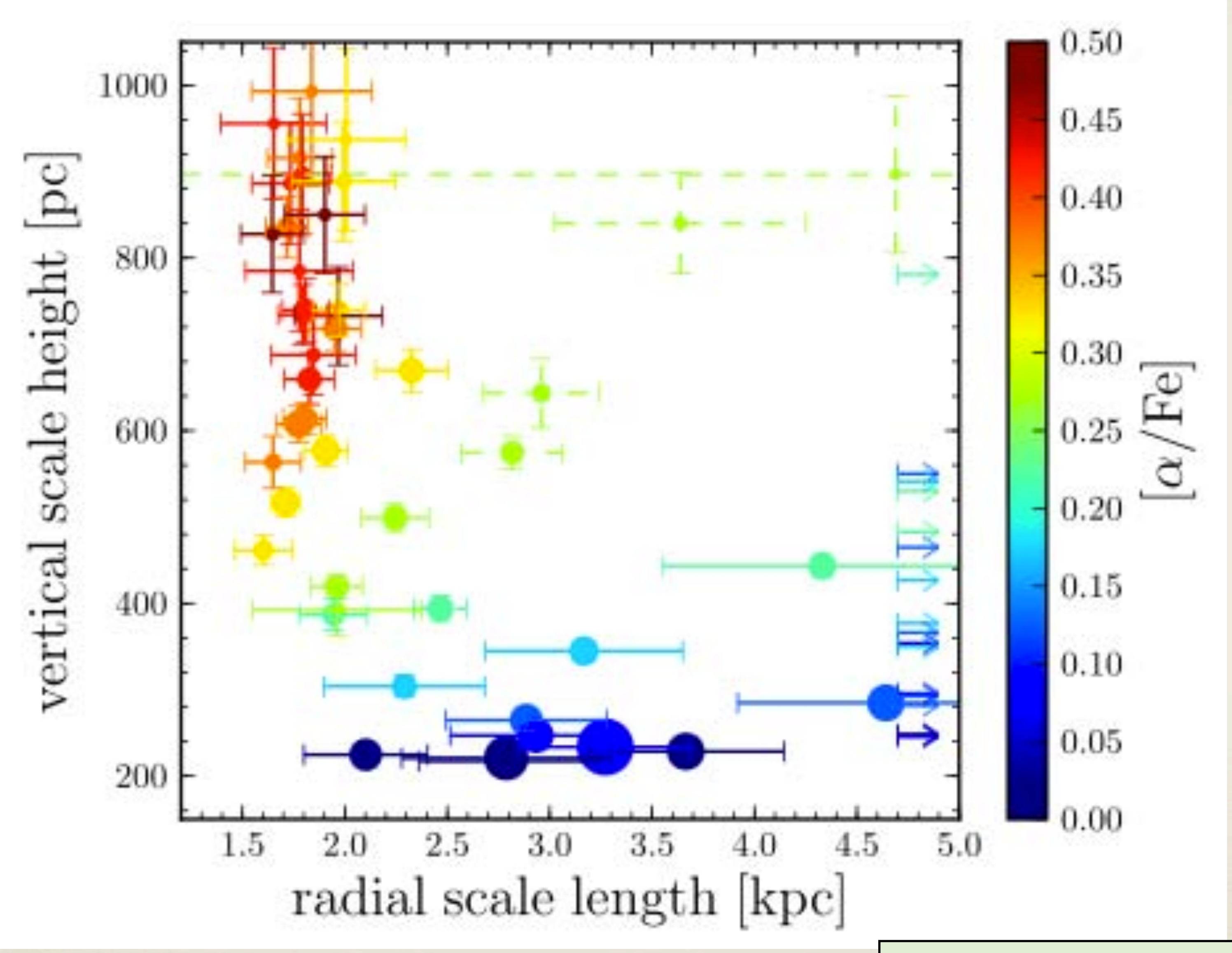
Thick disks are **extended**

NGC



Streich et al. (in prep)

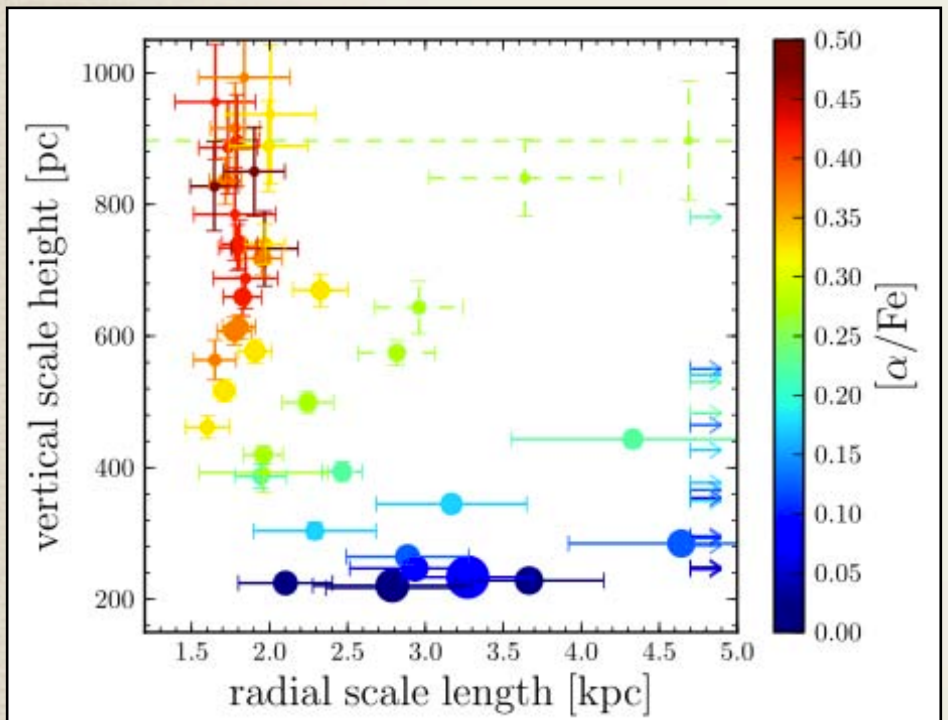
Chemically/Age defined Milky Way thick disk **centrally concentrated** (e.g., not extended)



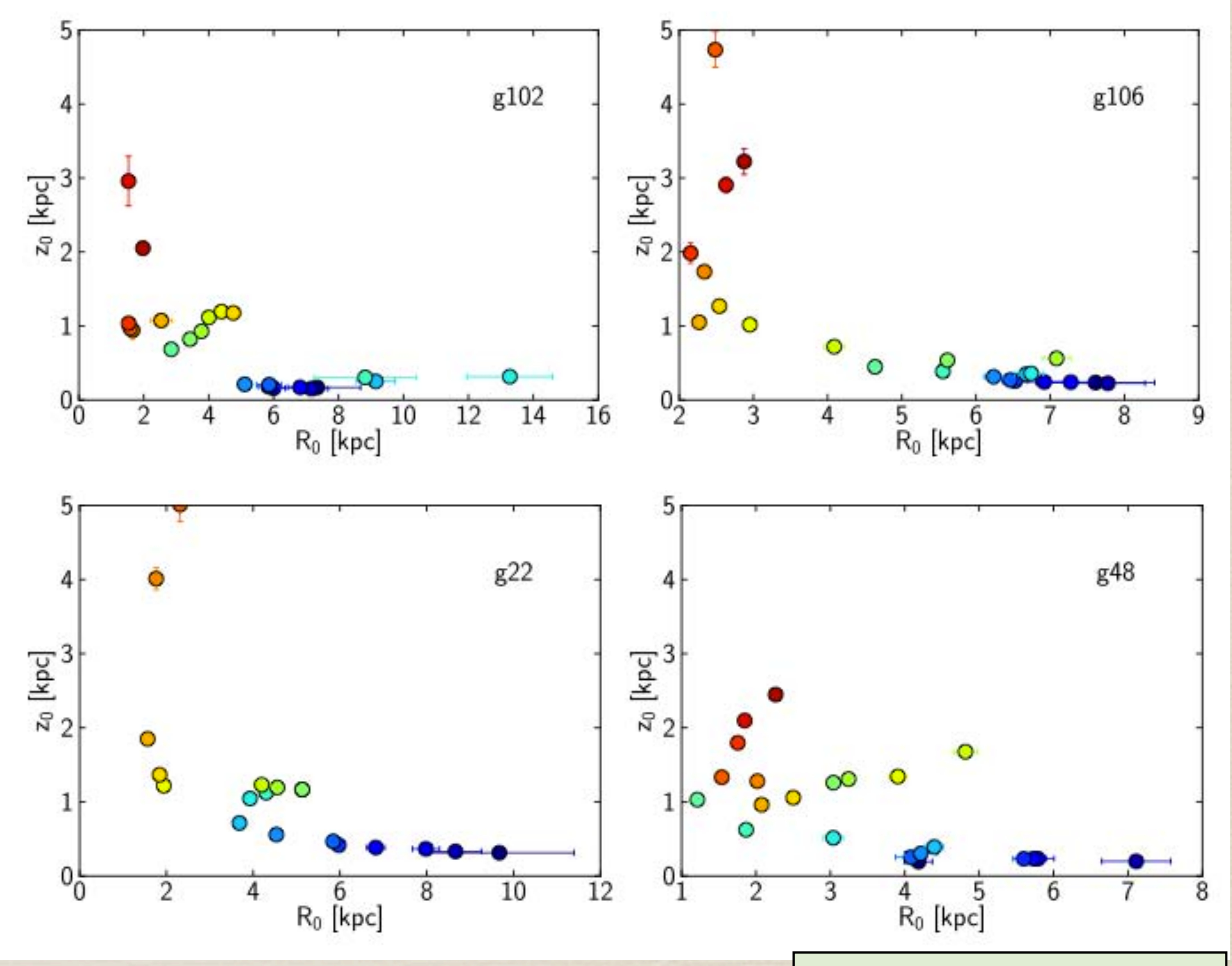
Bovy et al. (2012a)

Chemically/Age defined Milky Way thick disk **centrally concentrated** (e.g., not extended)

Simulations with strong merger activity at high redshift



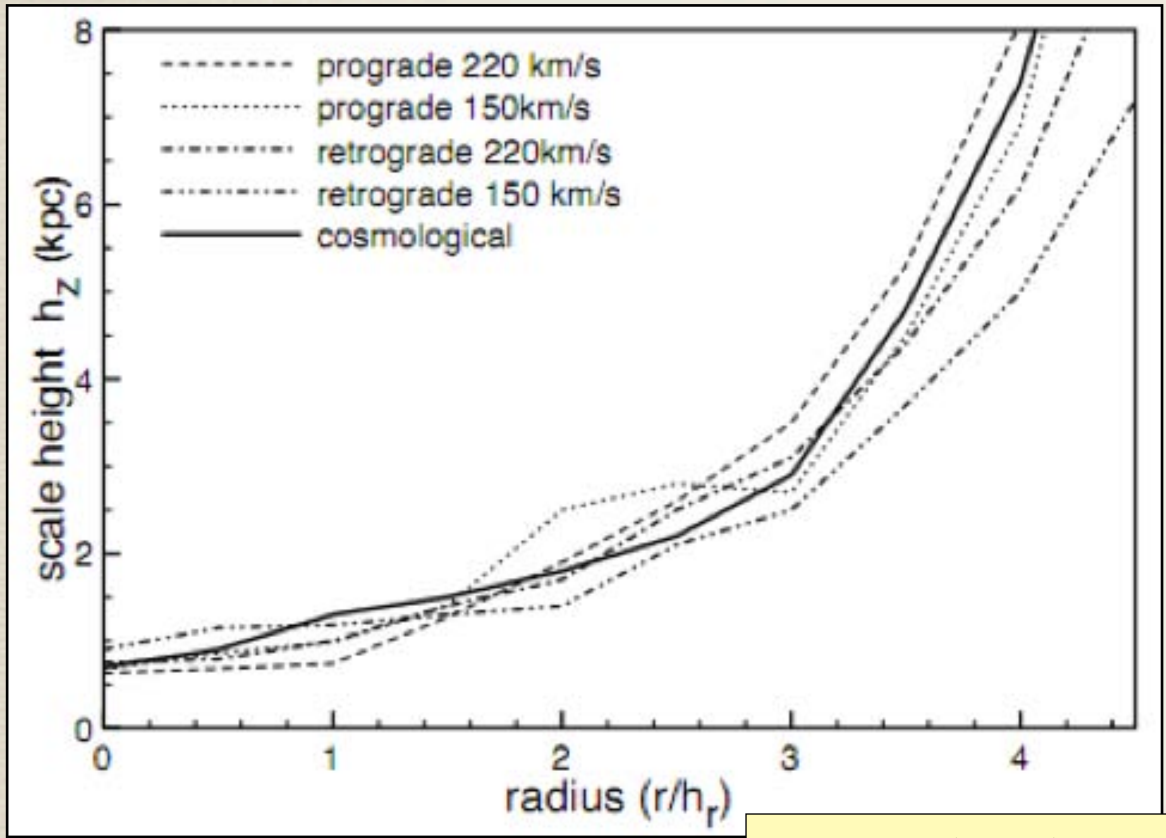
Bovy et al. (2012a)



Martig et al. (2014a)

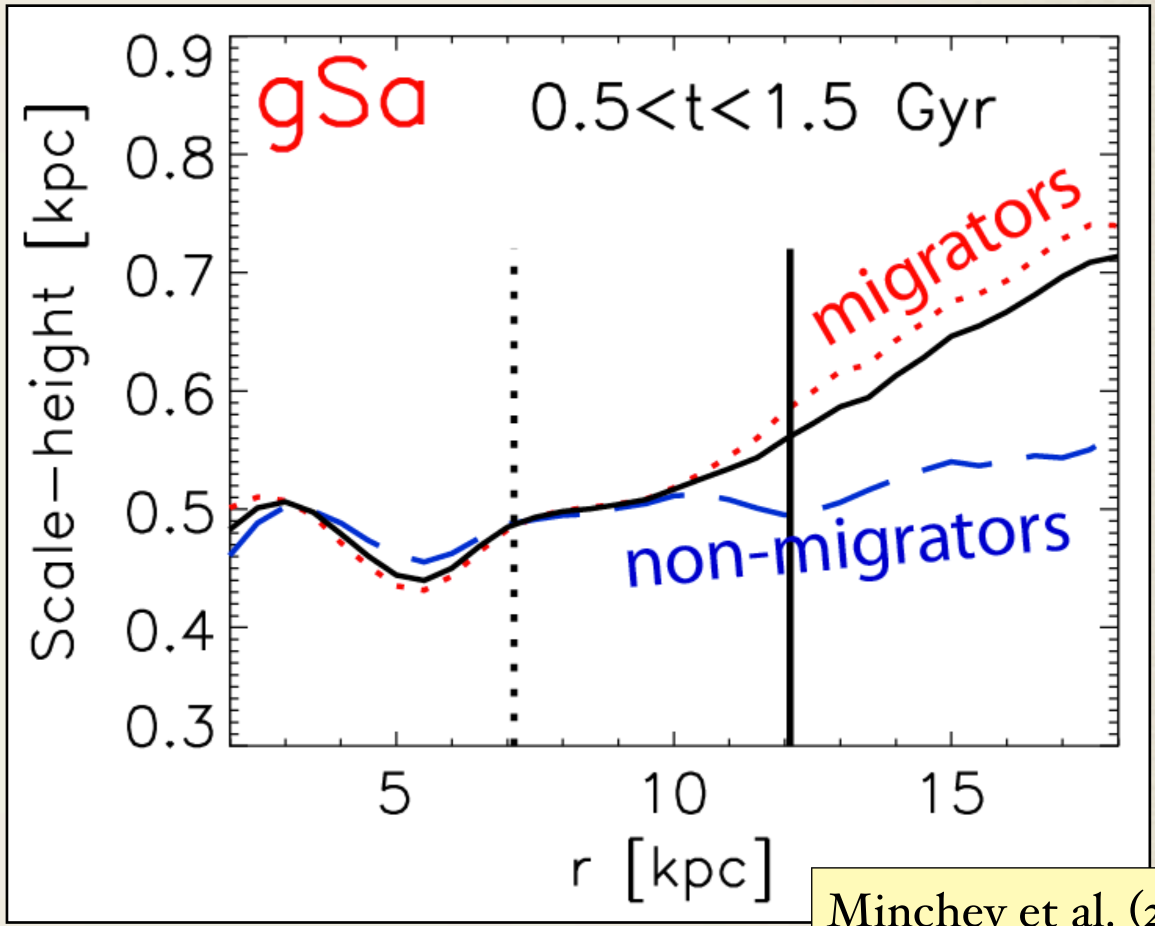
Simulated disks **always flare** (for a single stellar population)

Mergers flare disks



Bournaud et al. 2009

Migration flares disks

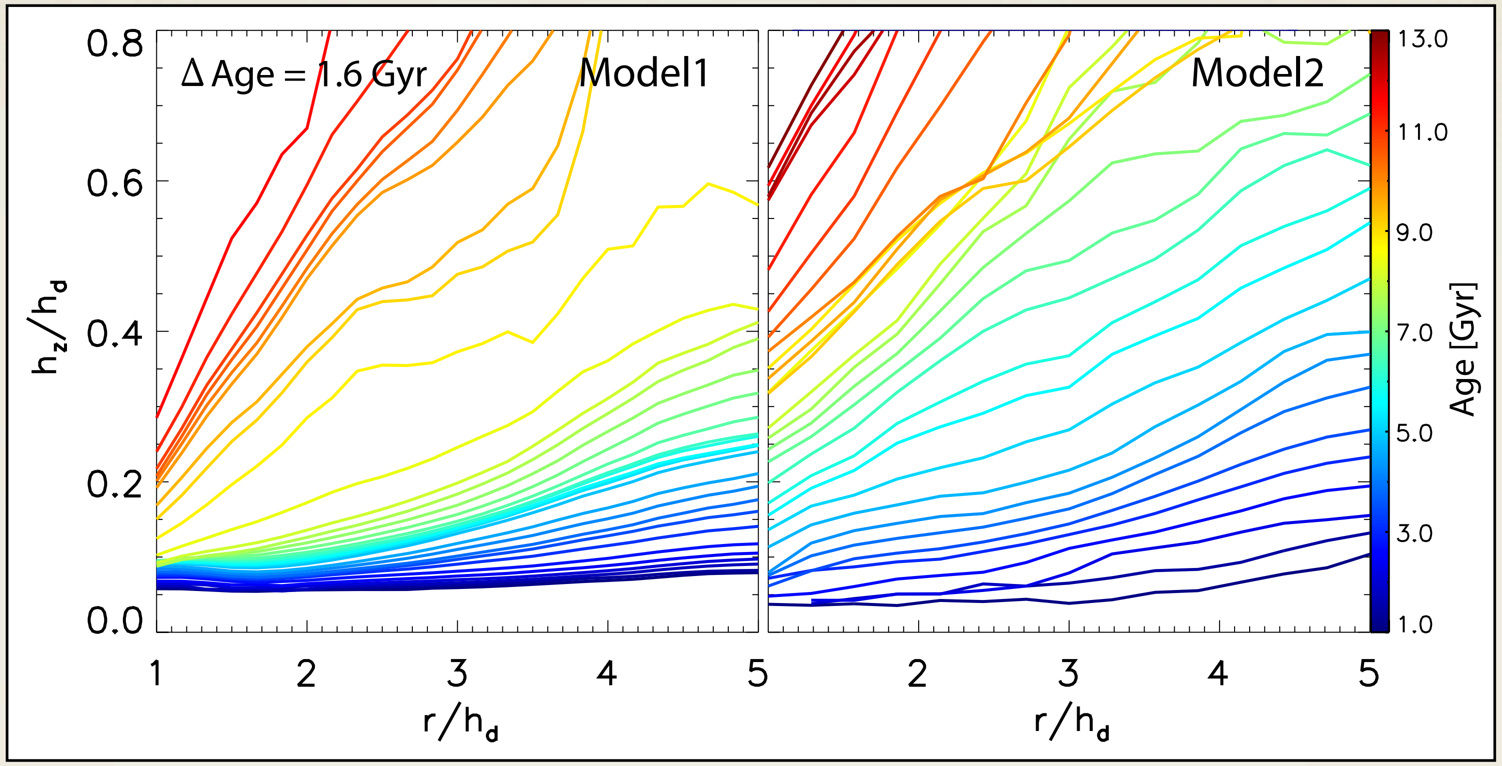


Minchev et al. (2012)

But observed edge-on disks do not flare (de Grijs 1998; Comerón et al. 2011)!

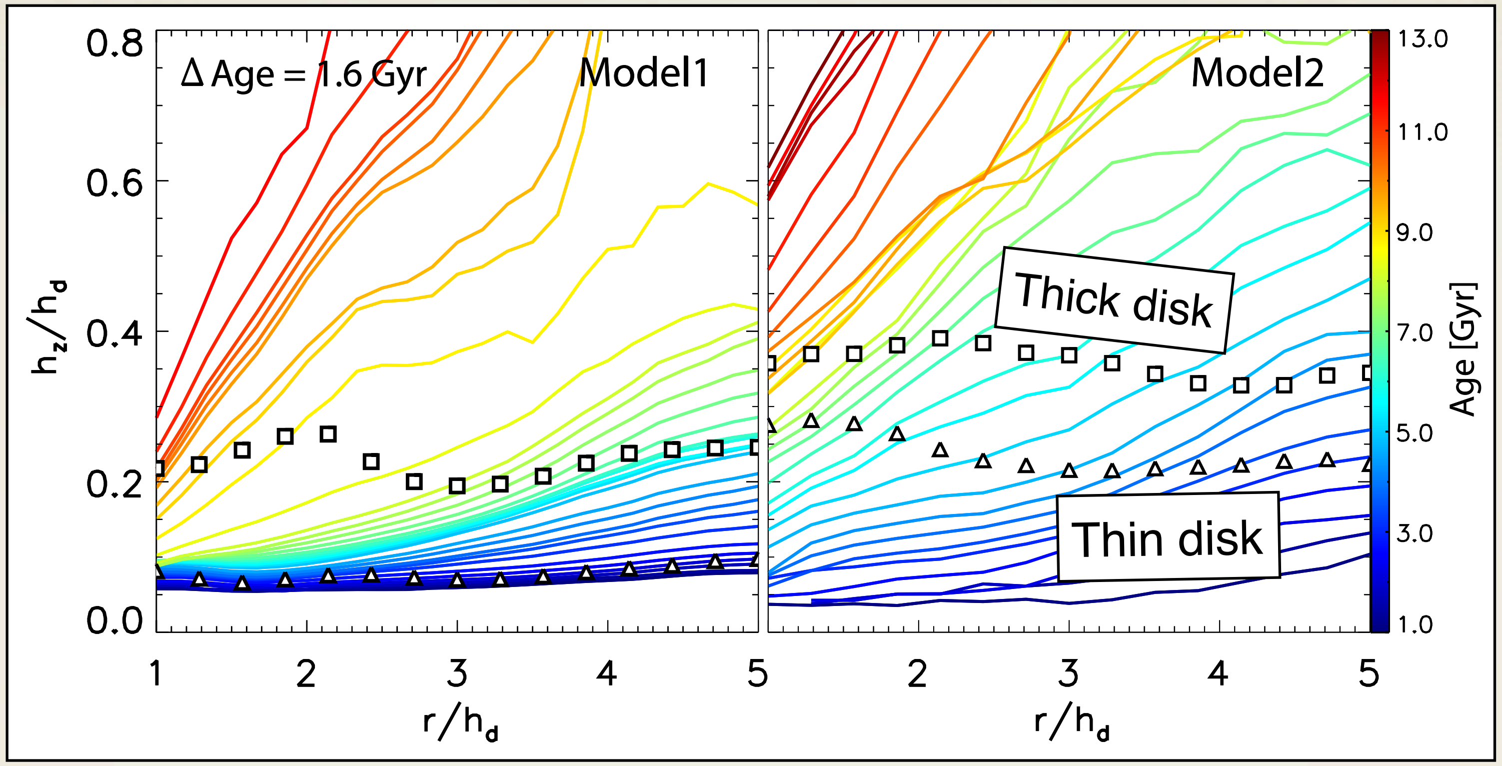
Disk flaring in inside-out formation

Martig sims   Scannapieco sims



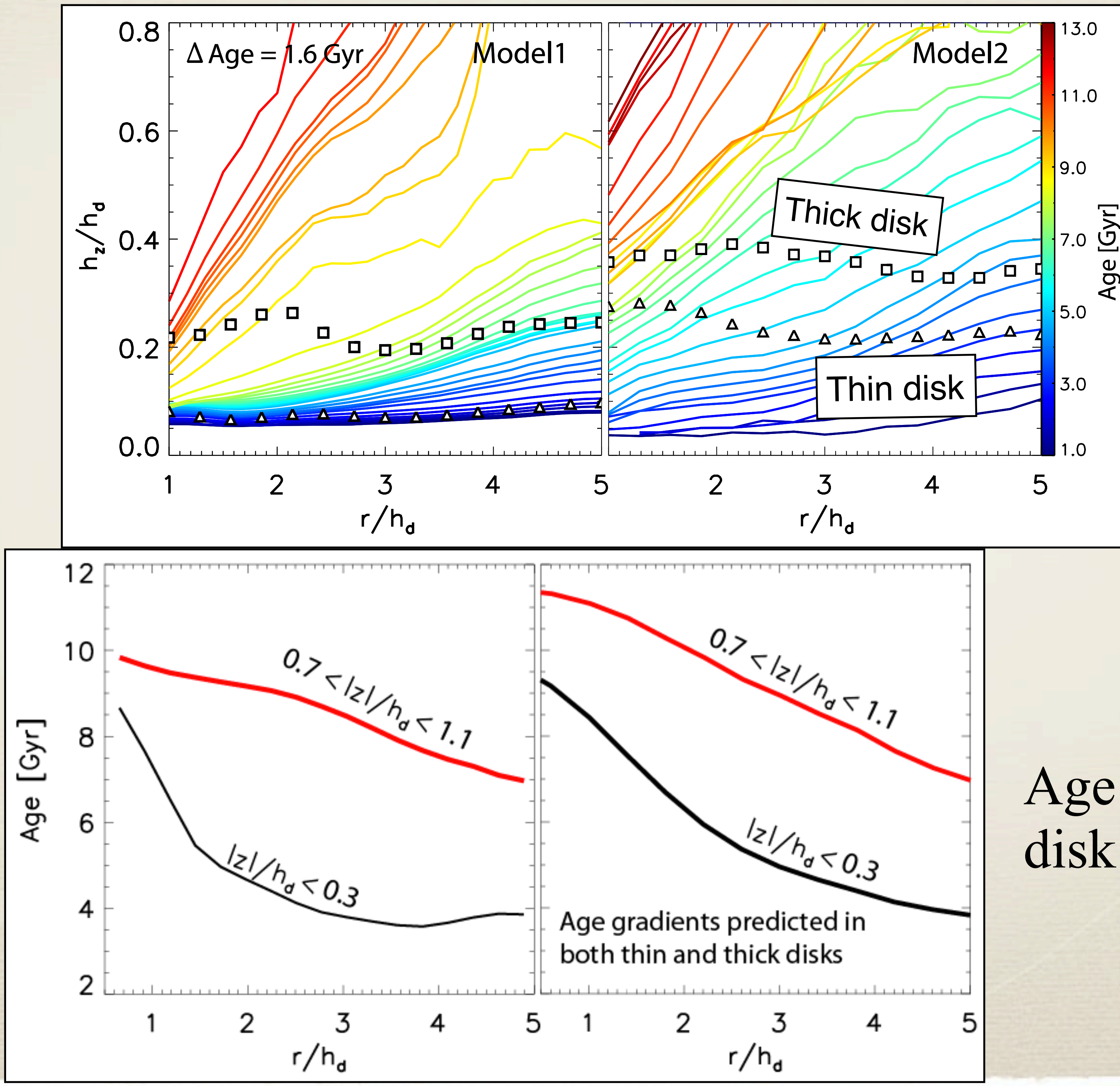
Disk flaring in inside-out formation

Martig sims Scannapieco sims



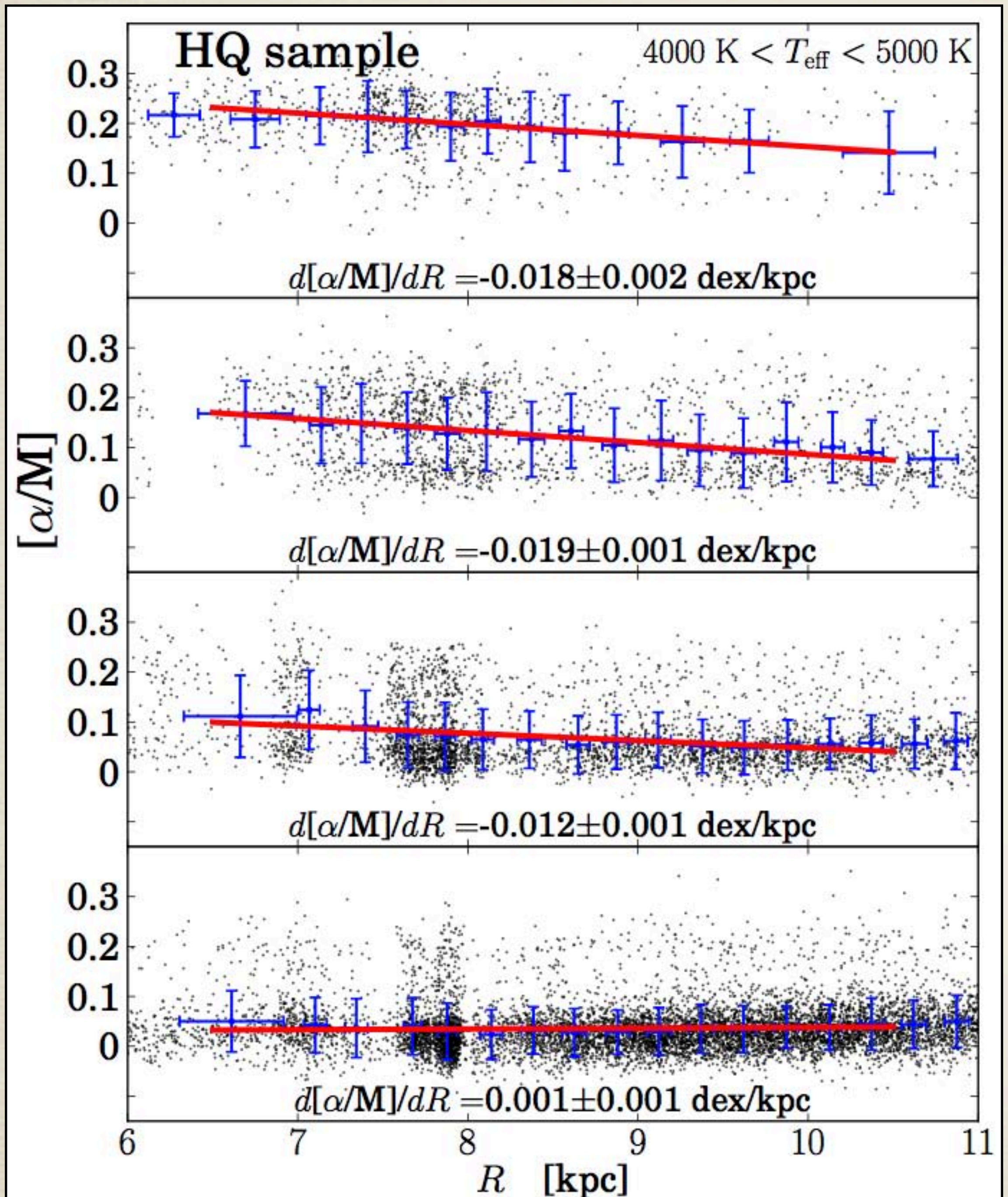
The structure of simulated thick disks

Martig sims　　Scannapieco sims



Age gradient in thick disk predicted

[α/Fe] gradient away from disk plane in APOGEE data



1.5 < |z| < 3.0 kpc

0.8 < |z| < 1.5 kpc

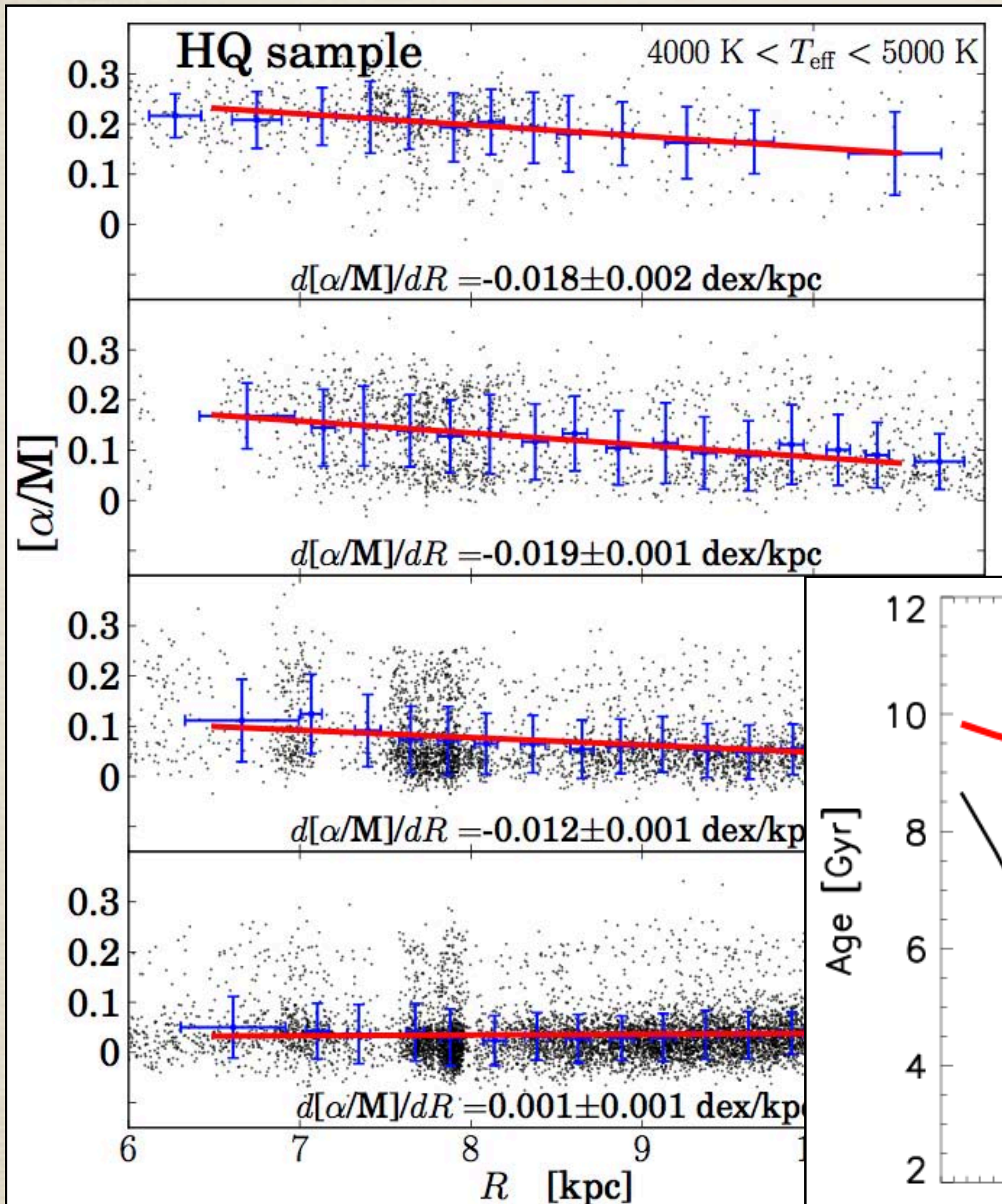
0.4 < |z| < 0.8 kpc

0.0 < |z| < 0.4 kpc

Distance from disk plane

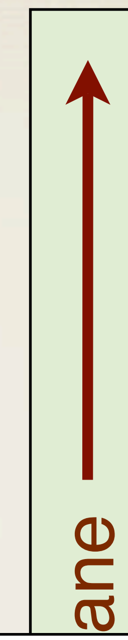
Anders + APOGEE (2014)

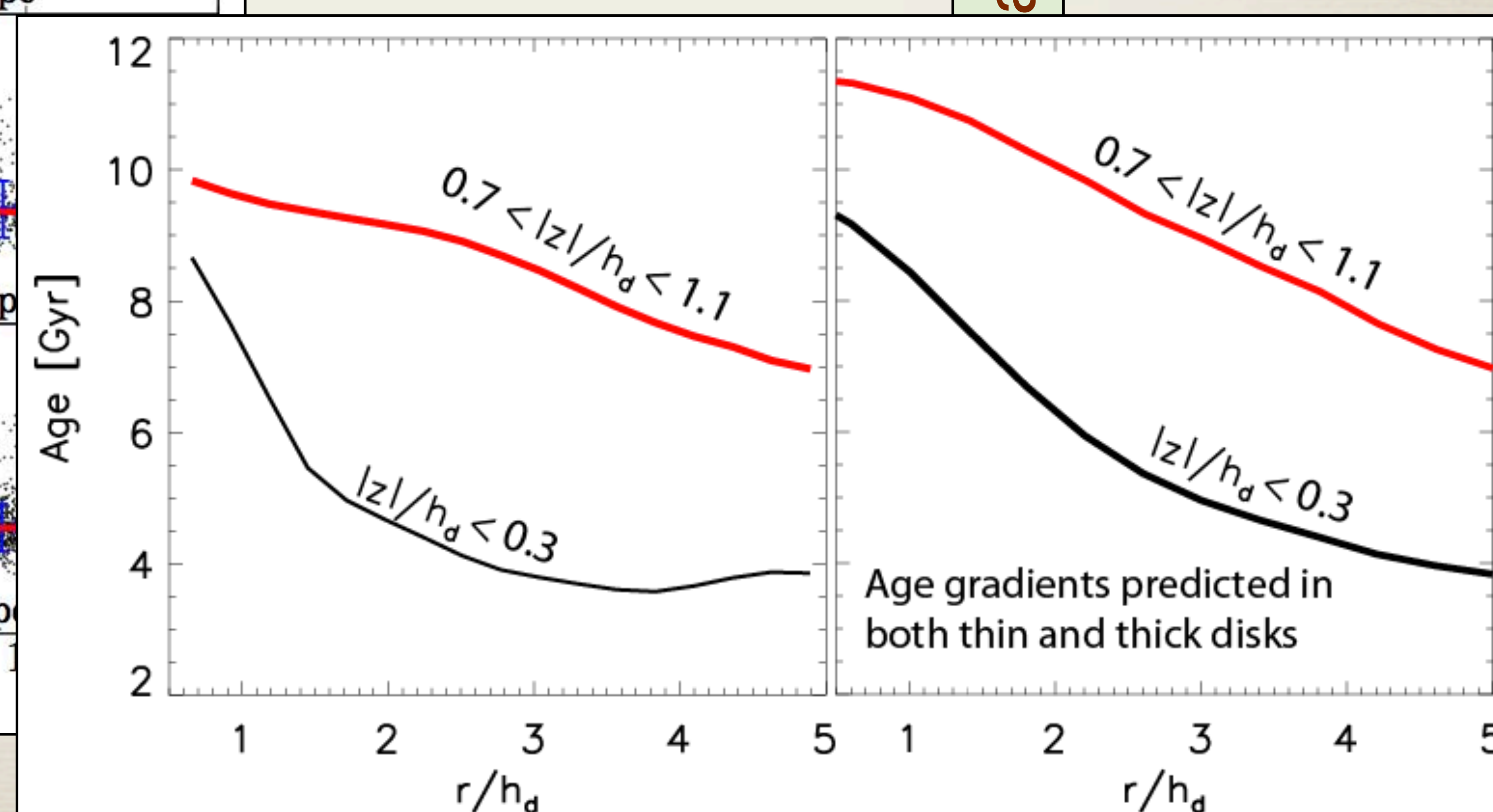
[α/Fe] gradient away from disk plane in APOGEE data



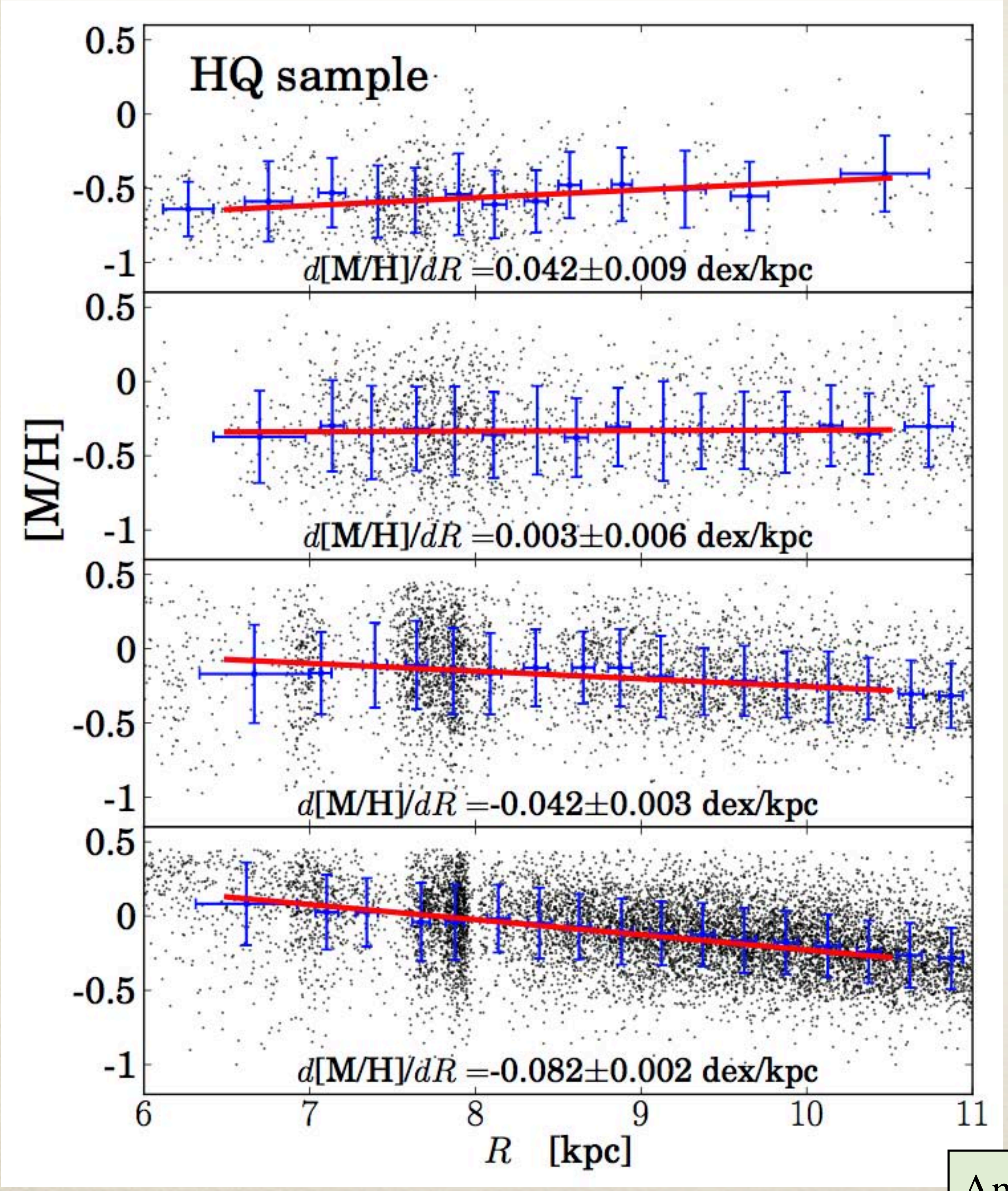
1.5 < |z| < 3.0 kpc

0.8 < |z| < 1.5 kpc



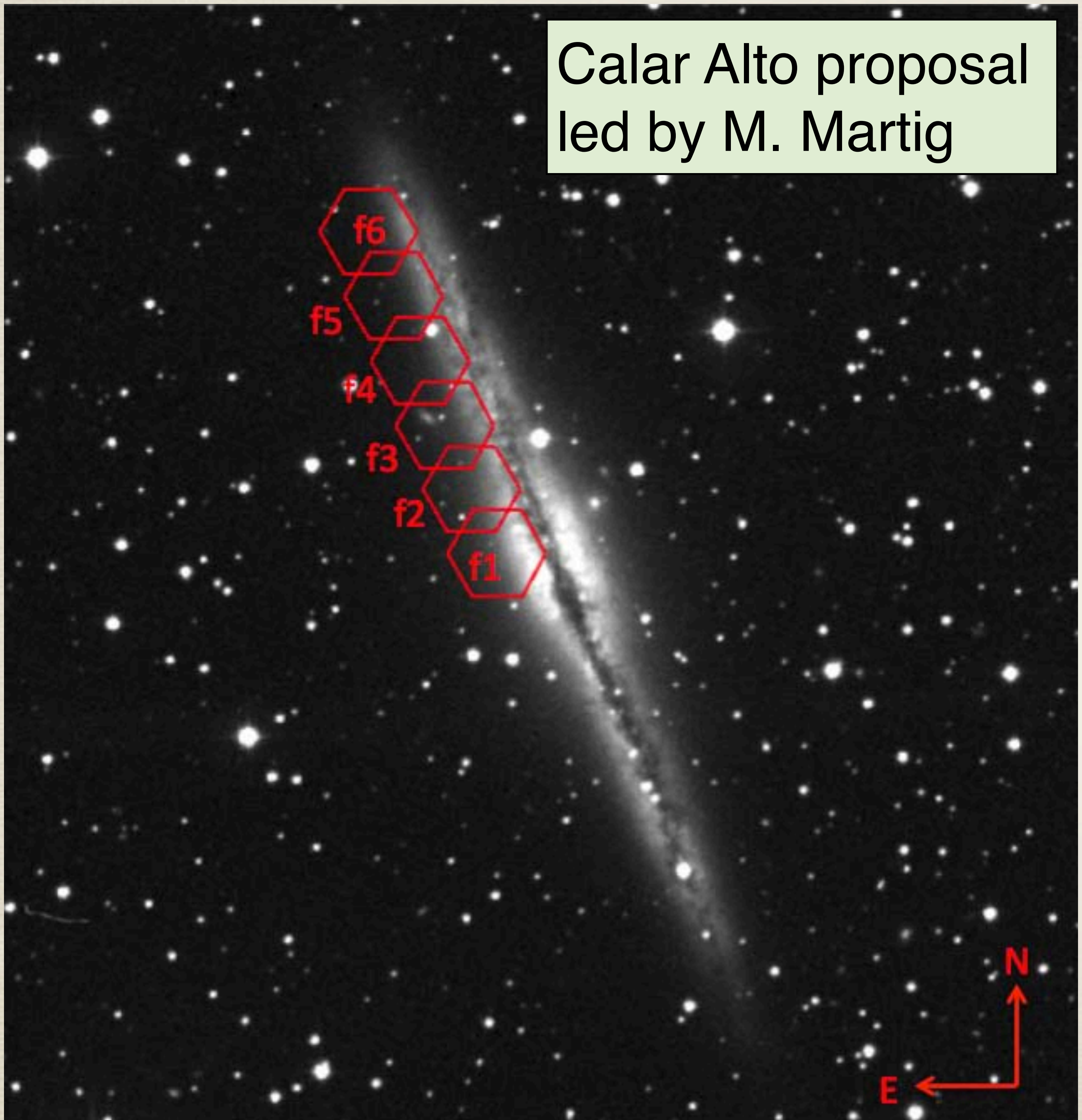


Inversion in metallicity gradients in APOGEE giants



Anders et al. (2014)

[α/Fe] gradient in the thick disk of NGC891?



Calar Alto data currently being reduced (CALIFA)

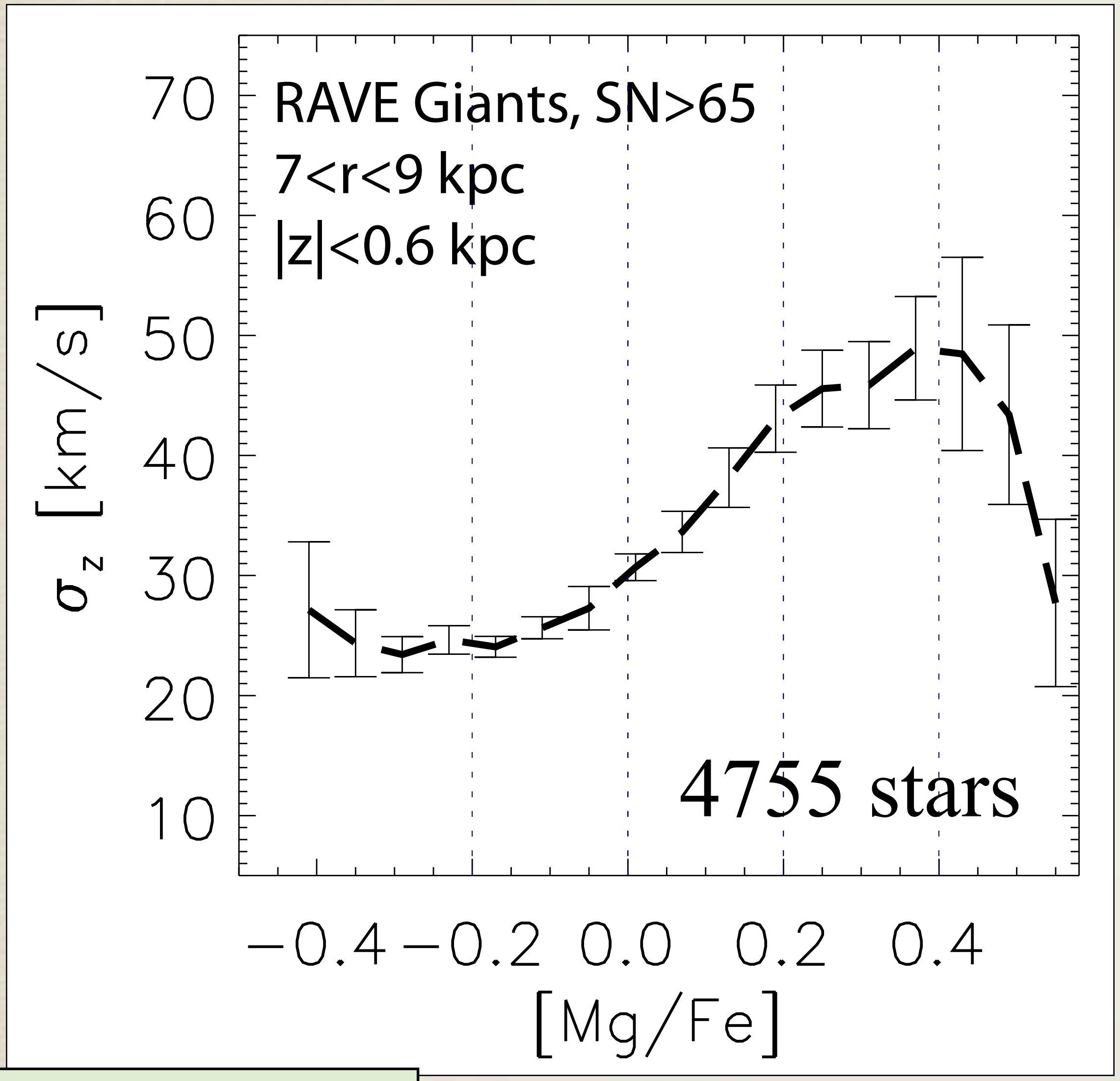
Approved MUSE on VLT proposal approved (PI M. Martig) for NGC 5746 and NGC 4710

Summary

- Great improvements in chemo-dynamics in cosmological simulations, however, still hard to apply to Milky Way.
- Our hybrid chemo-dynamical model consistent with a wide range of observational constraints.
  - Great care taken in defining properly the solar radius.
  - Technique can be used to probe a range of chemical evolution histories.
  - More than 30 elements available for doing Galactic Archeology (e.g., GALAH, APOGEE, Gaia + 4MOST+WEAVE).
- Thick disks composed of the flares of populations of different ages:
  - explains extended morphologically defined thick disks in external galaxies.
  - explains the centrally concentrated older populations in the MW.
  - explains the inversion of metallicity and [α/Fe] gradients away from disk midplane.

A new chemo-kinematic relation can recover the disk merger history

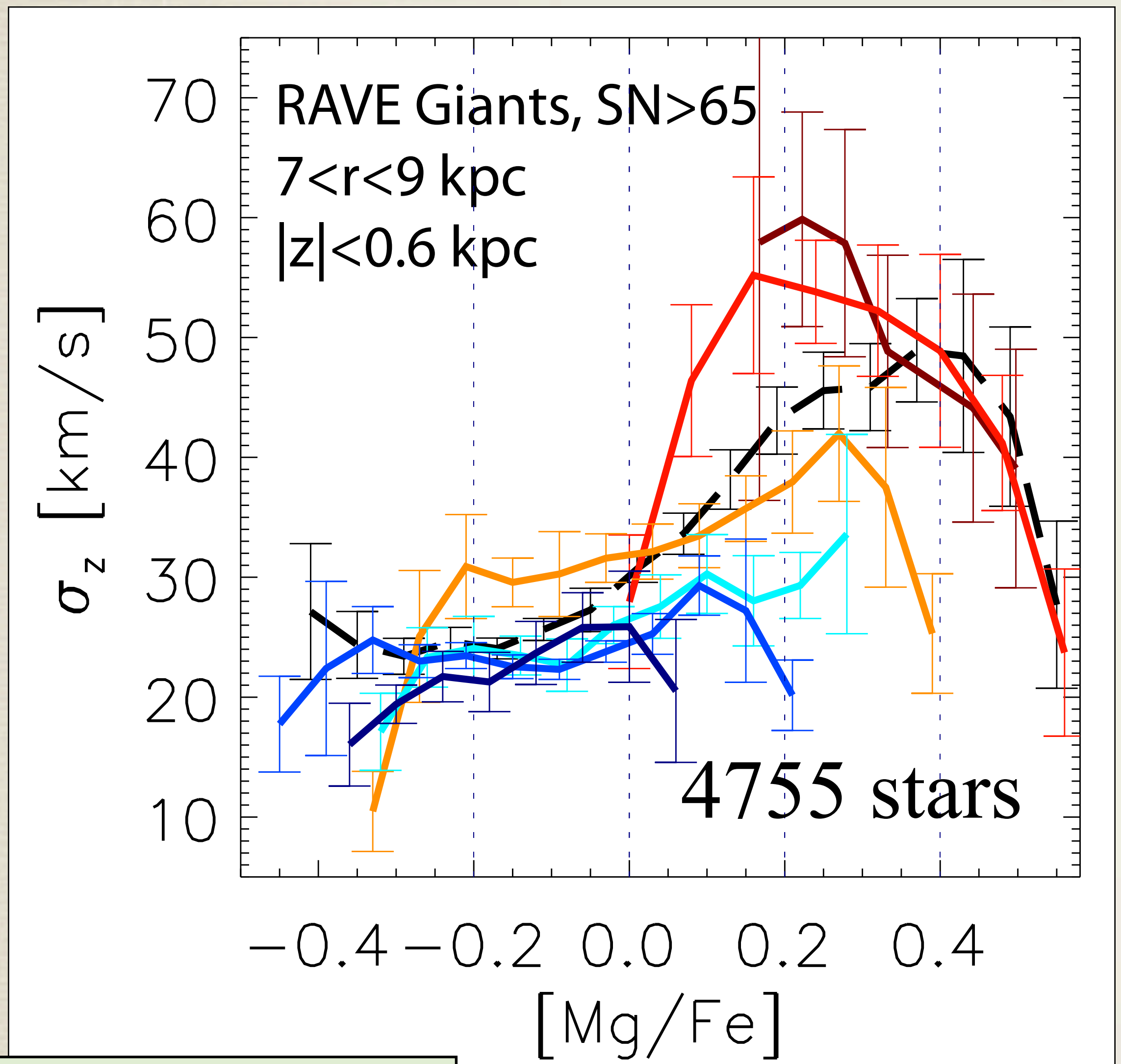
Vertical velocity dispersion as a fn of [Mg/Fe] in RAVE



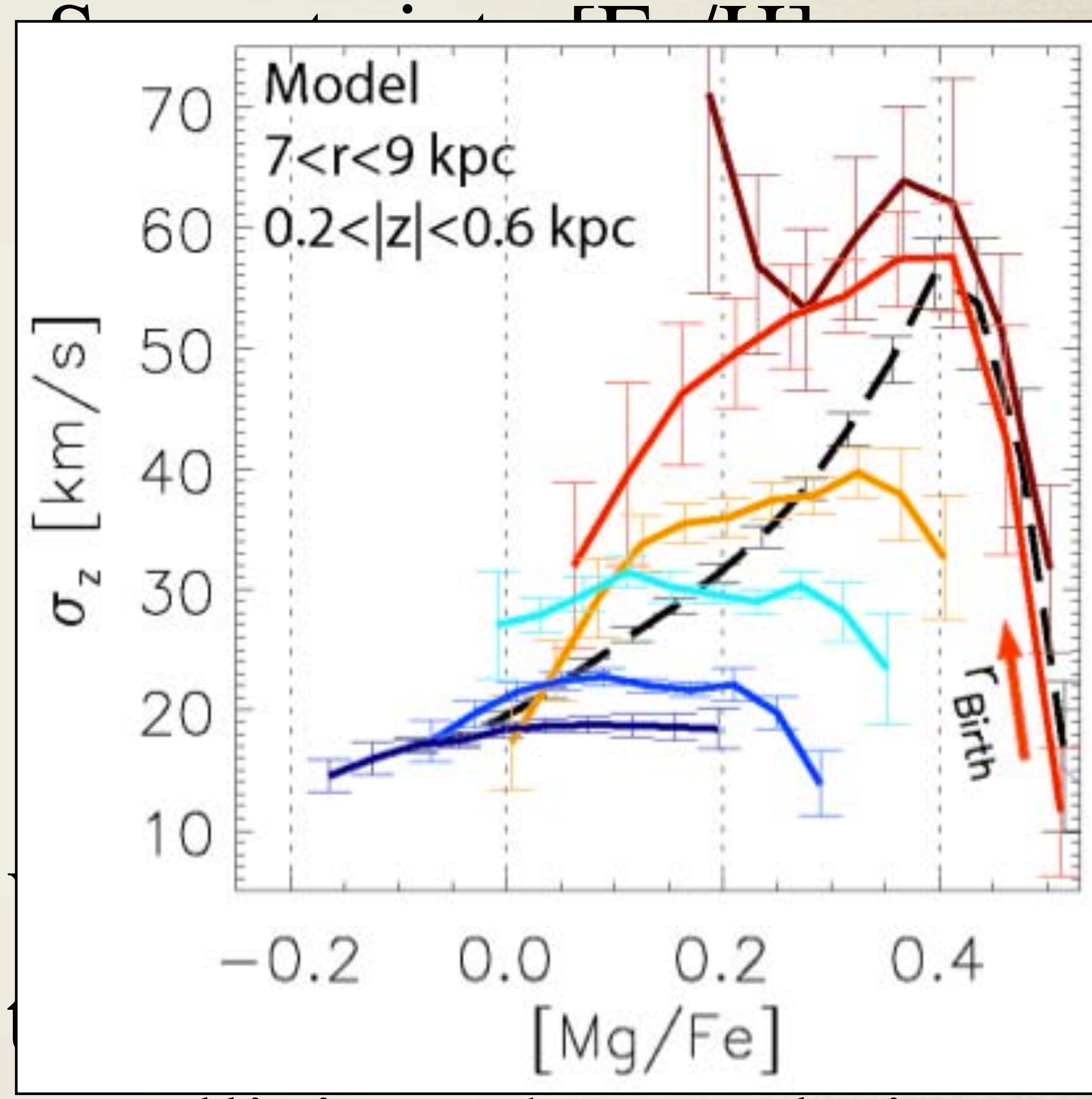
Minchev + RAVE (2014)

Velocity dispersion drops at [Mg/Fe] > 0.4 dex

Vertical velocity dispersion as a fn of [Mg/Fe] in RAVE

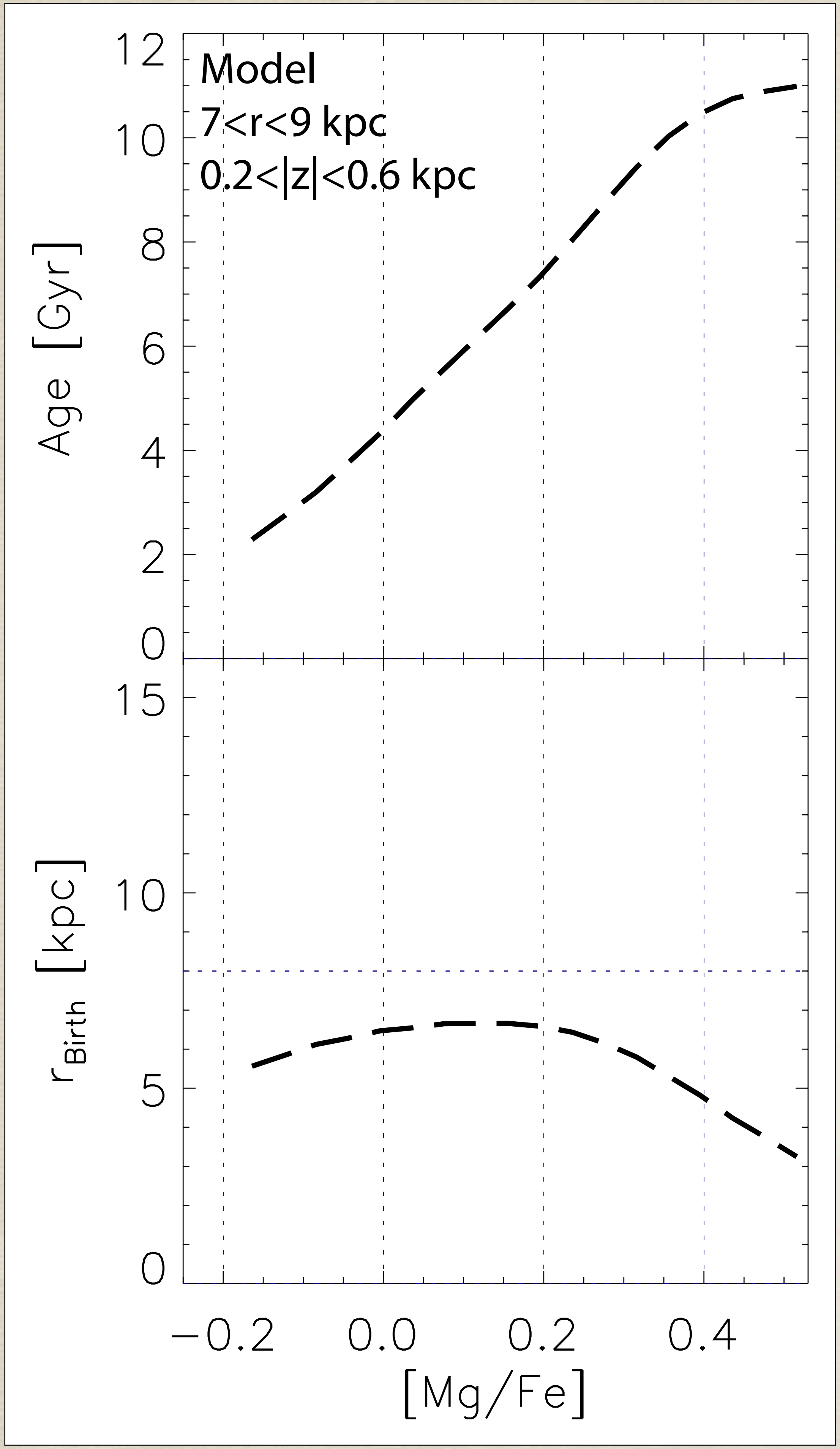


Minchev + RAVE (2014)

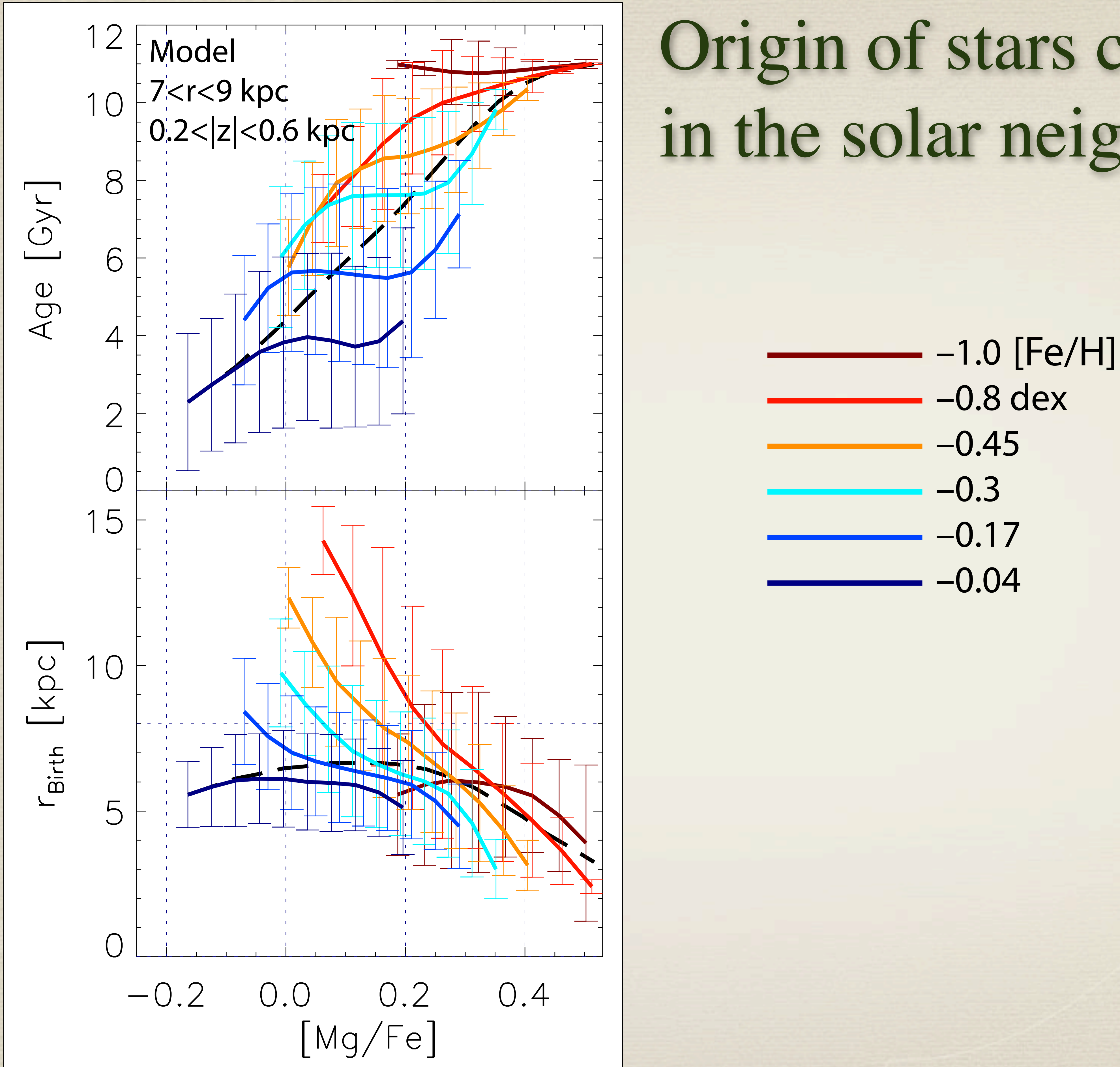


metallicity sub-population

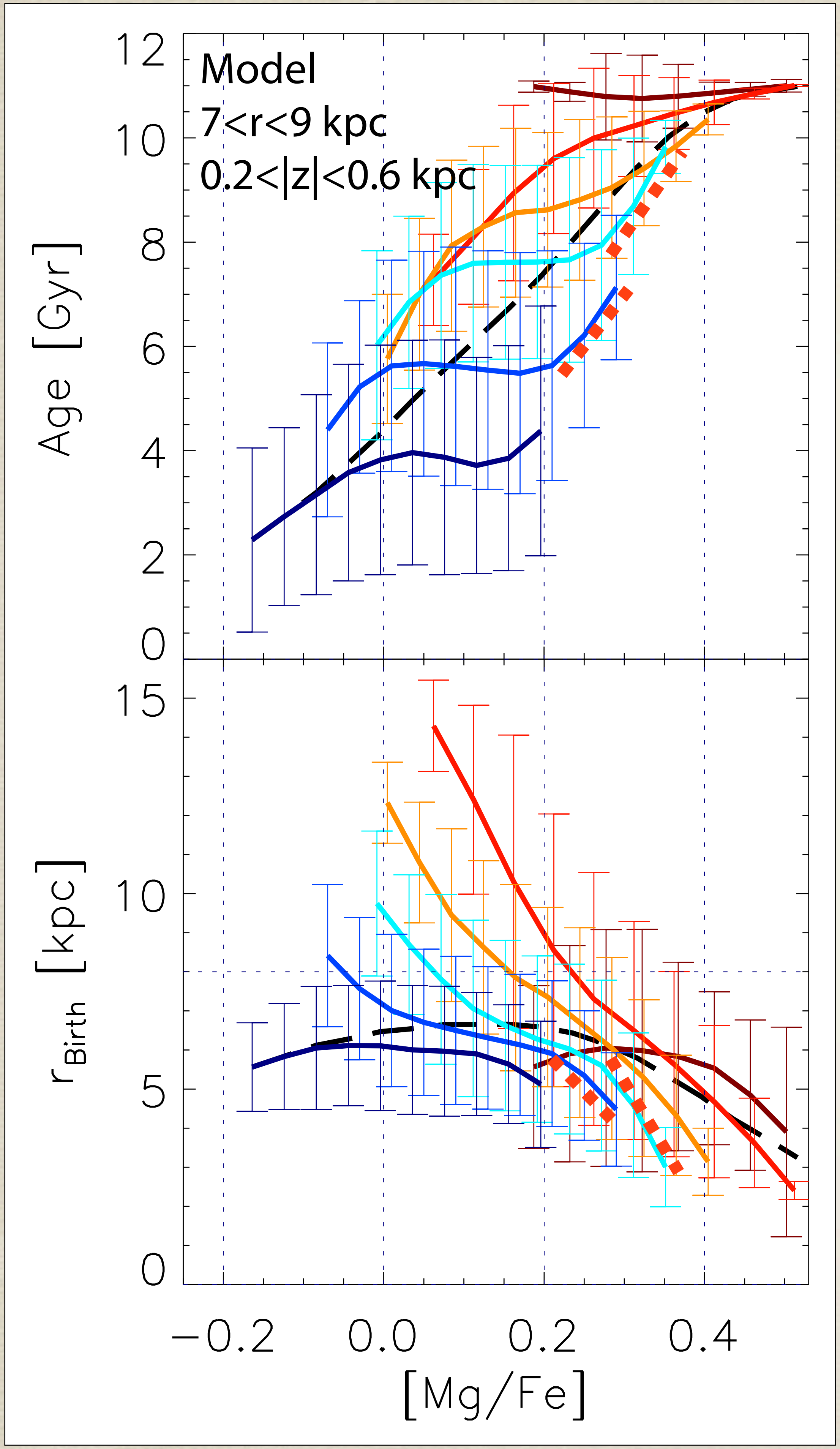
Origin of stars currently in the solar neighborhood

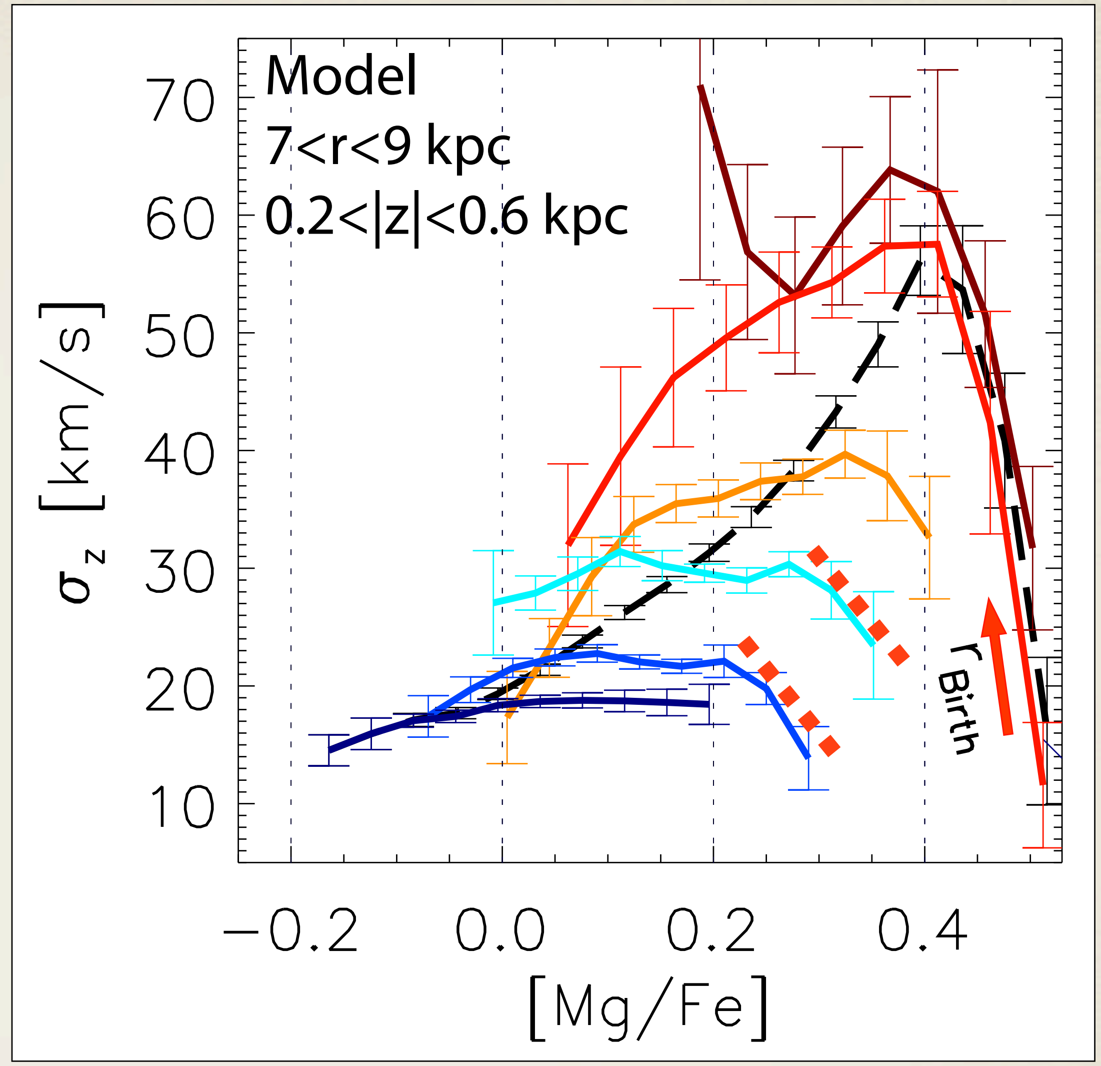


Origin of stars currently in the solar neighborhood



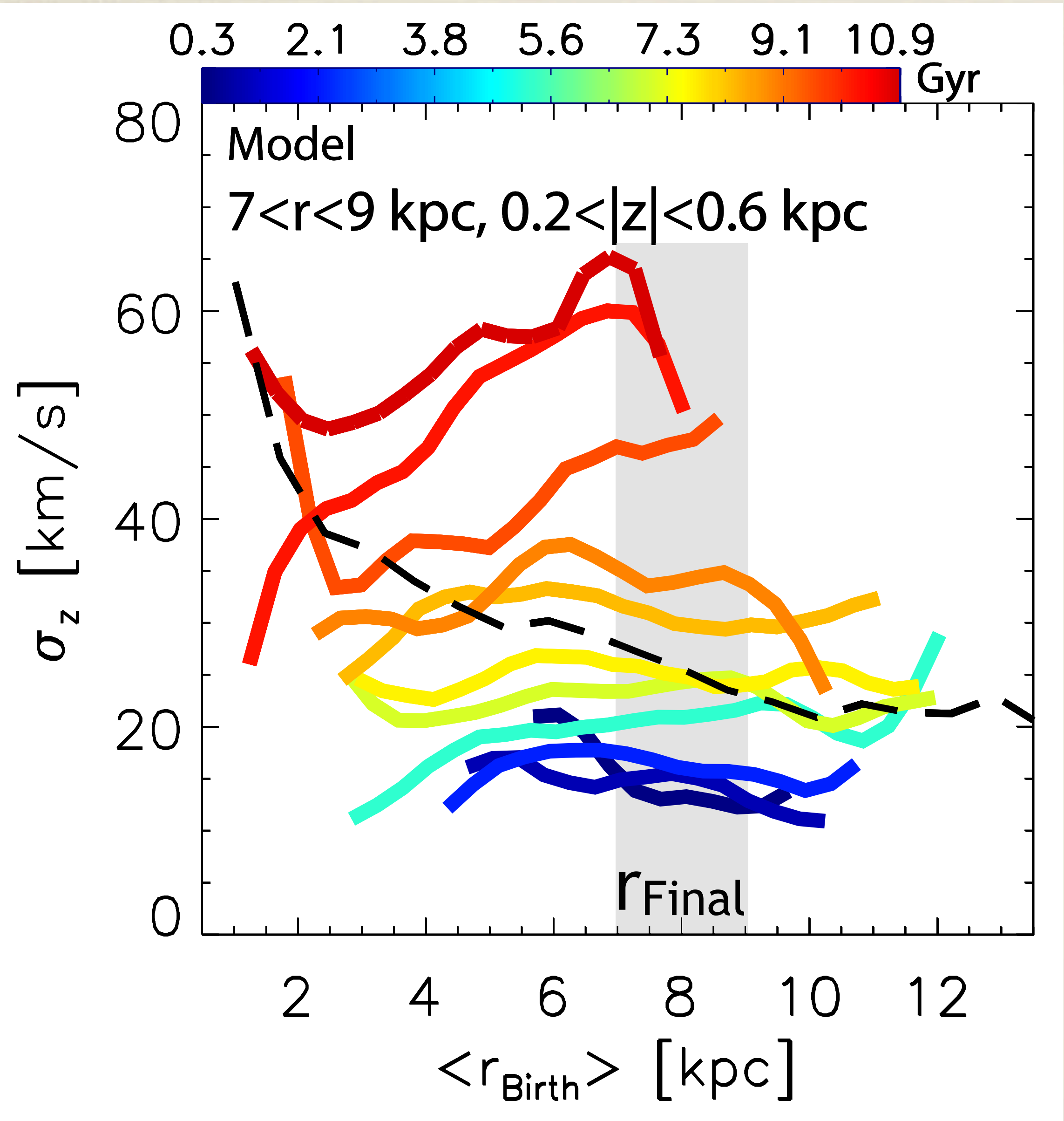
Origin of stars currently in the solar neighborhood





For a given metallicity bin, stars coming from the inner disc are kinematically colder and older.

Cool old stars arrive from inner disk during mergers

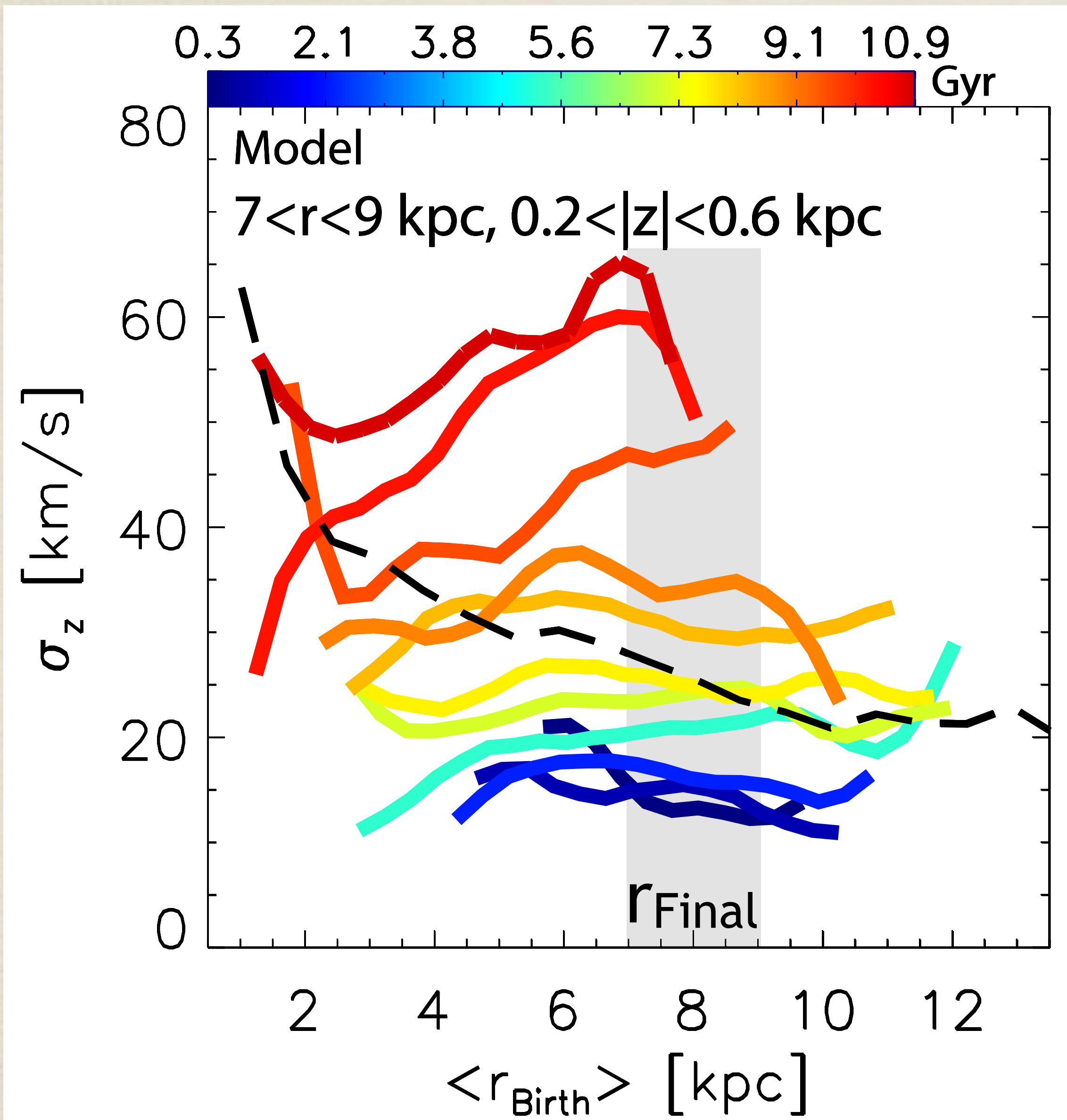


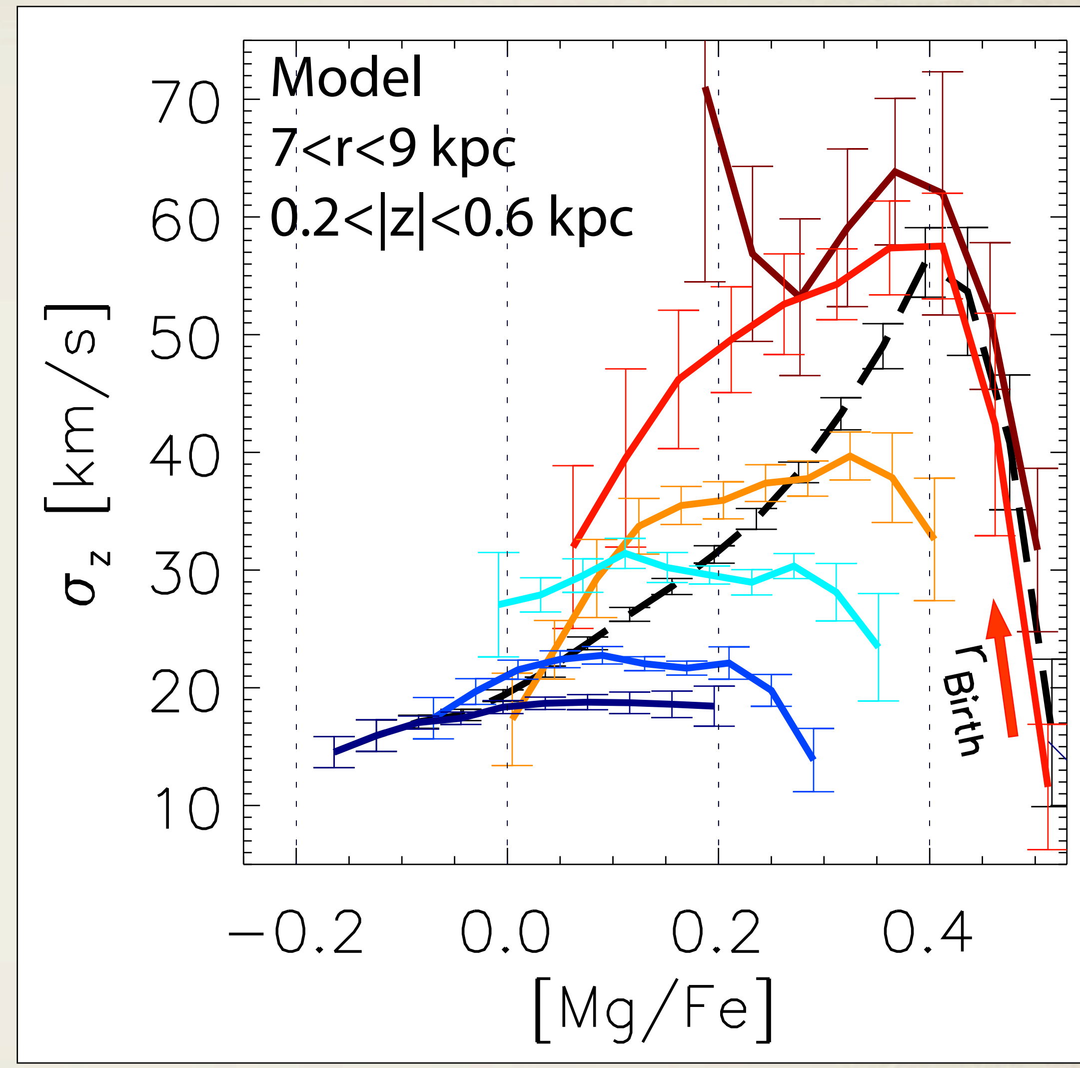
Old stars coming from the inner disk are cooler than locally born stars by up to 30 km/s.

Slope becomes negative for the last several Gyr (no significant mergers).

Explains inversion of vel. dispersion - [Mg/Fe] relation in RAVE and SEGUE G-dwarf data.

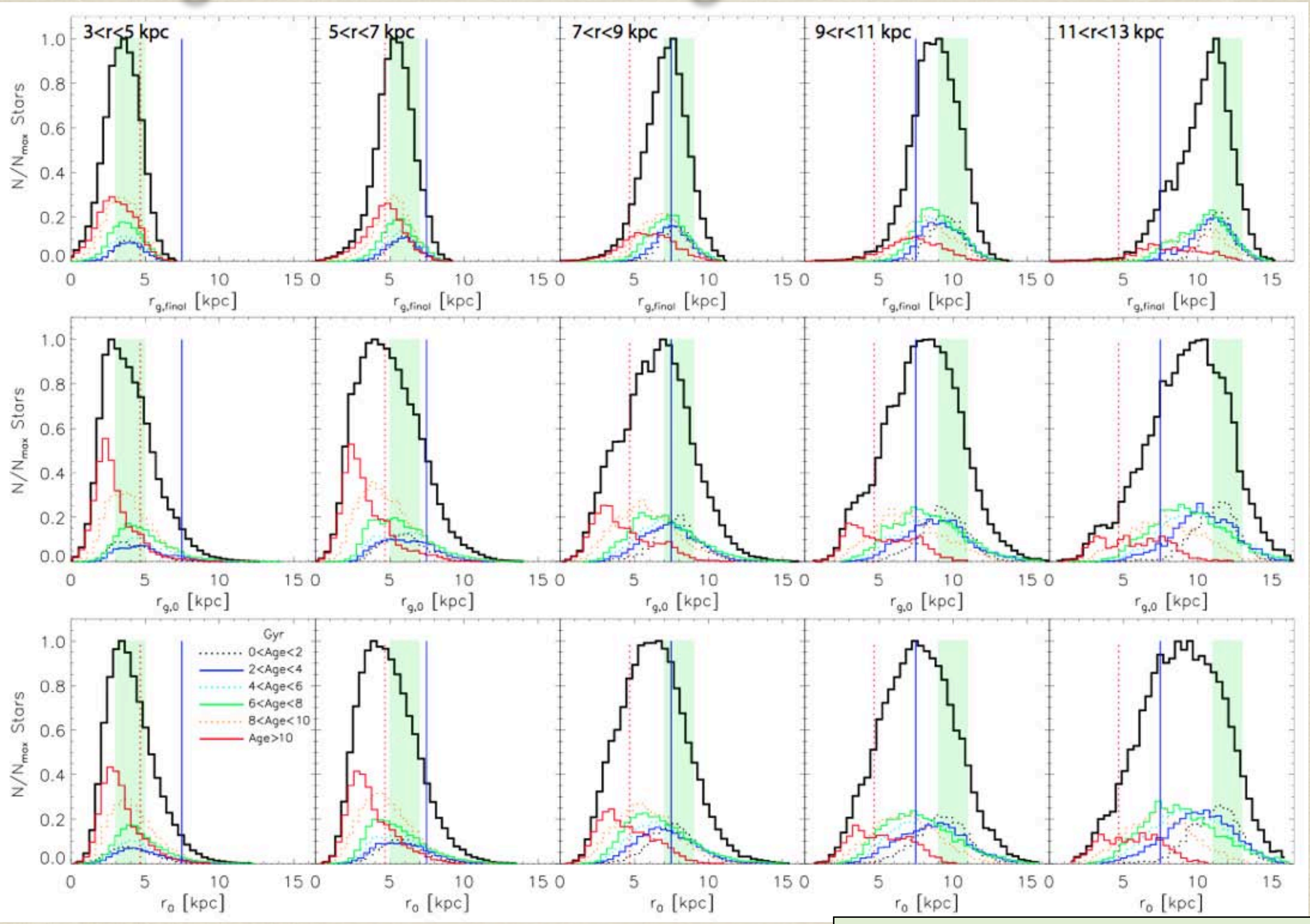
Cool old stars arrive from inner disk during mergers





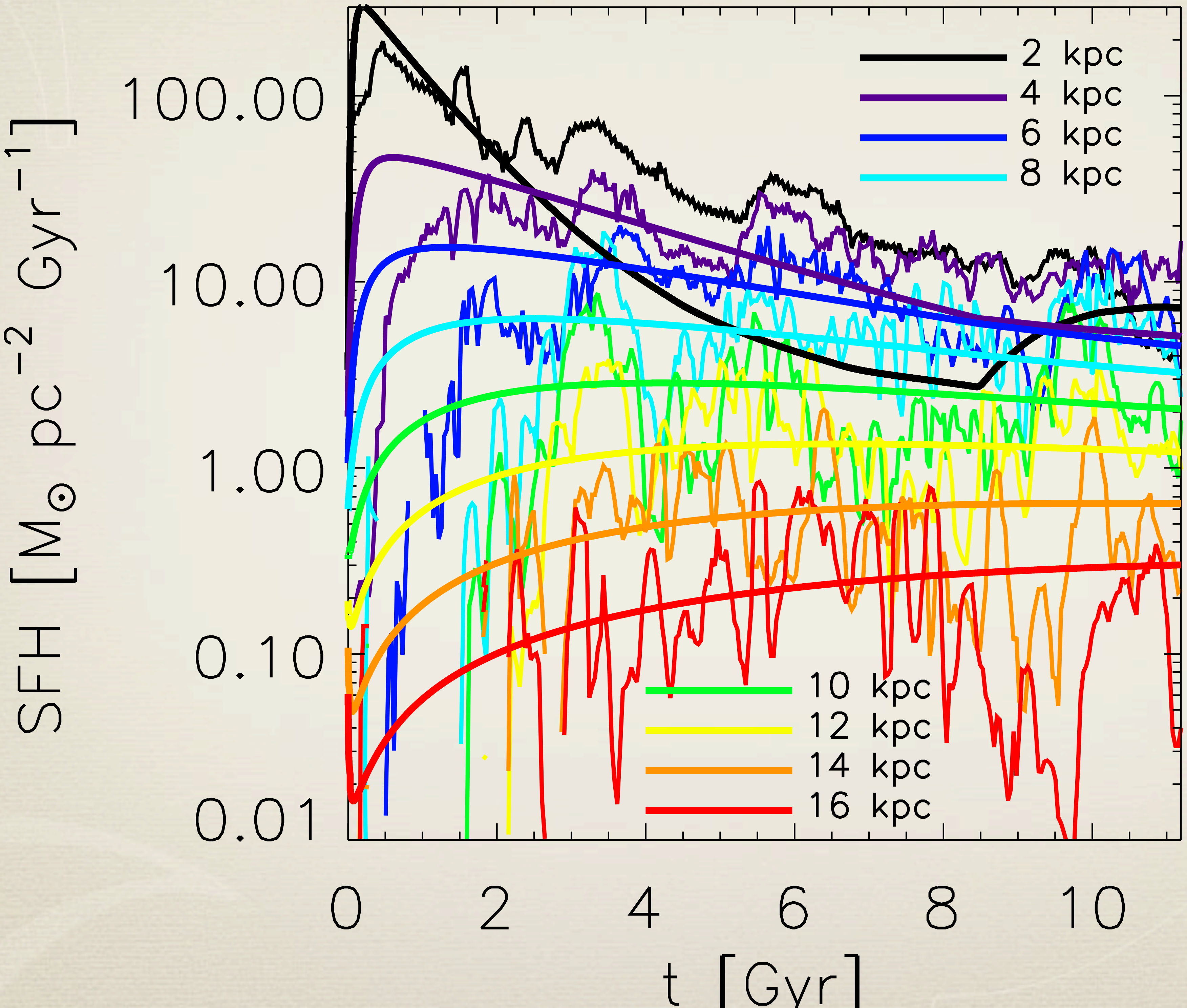
Explains inversion of vel. dispersion - [Mg/Fe] relation in RAVE and SEGUE G-dwarf data.

Migration vs blurring

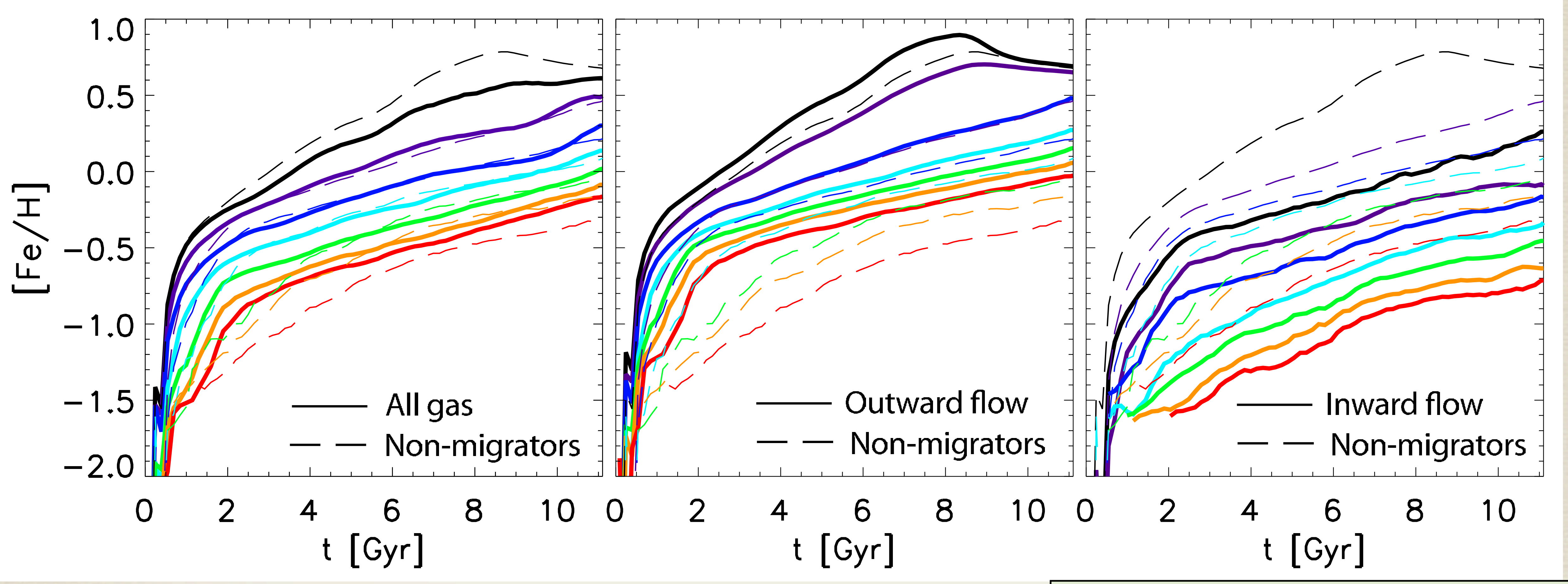


Minchev, Chiappini and Martig (2014)

Comparison between SFH in chemical model and in simulation



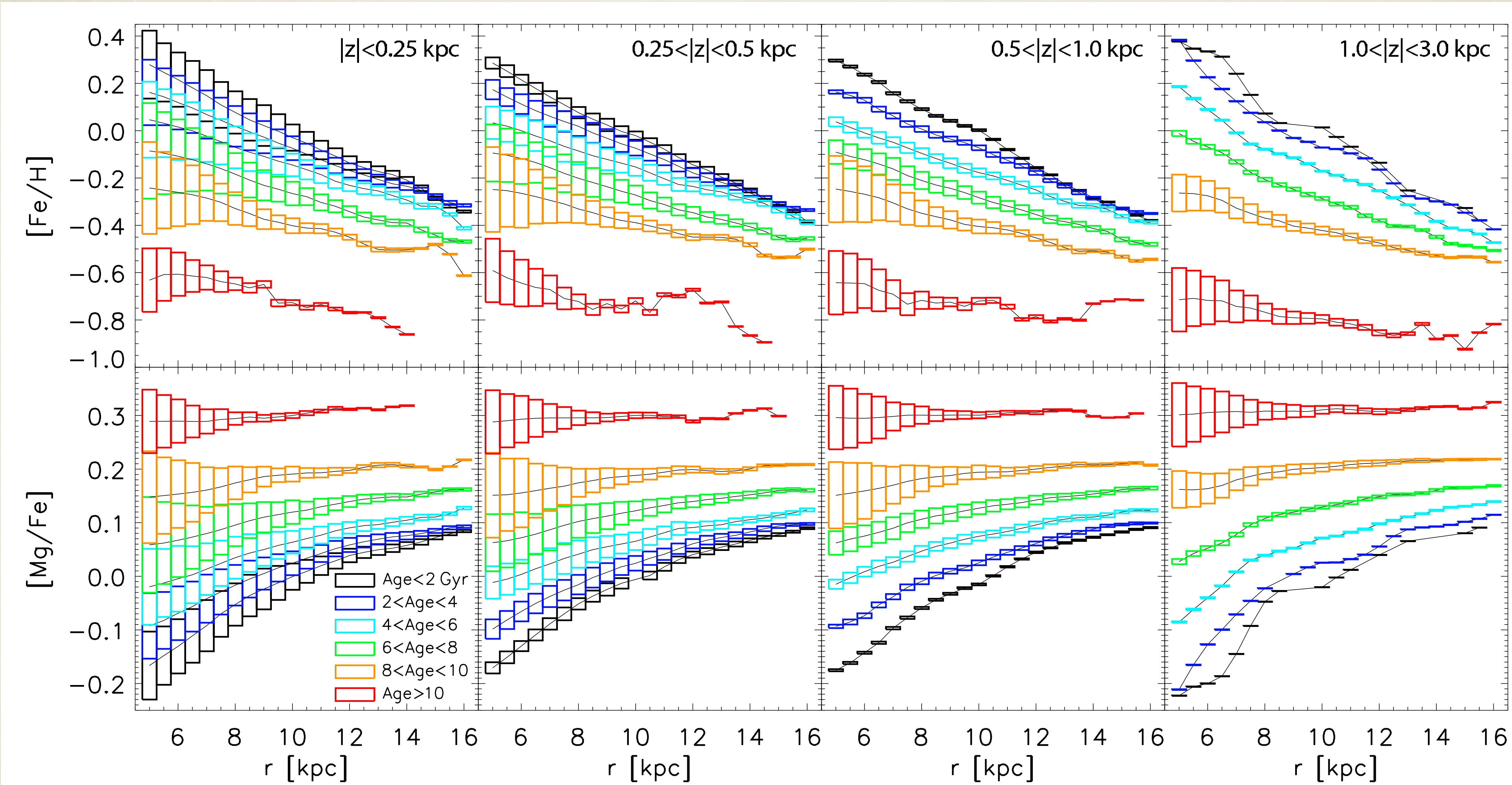
Recycled gas flows



Minchev, Chiappini & Martig (2014)

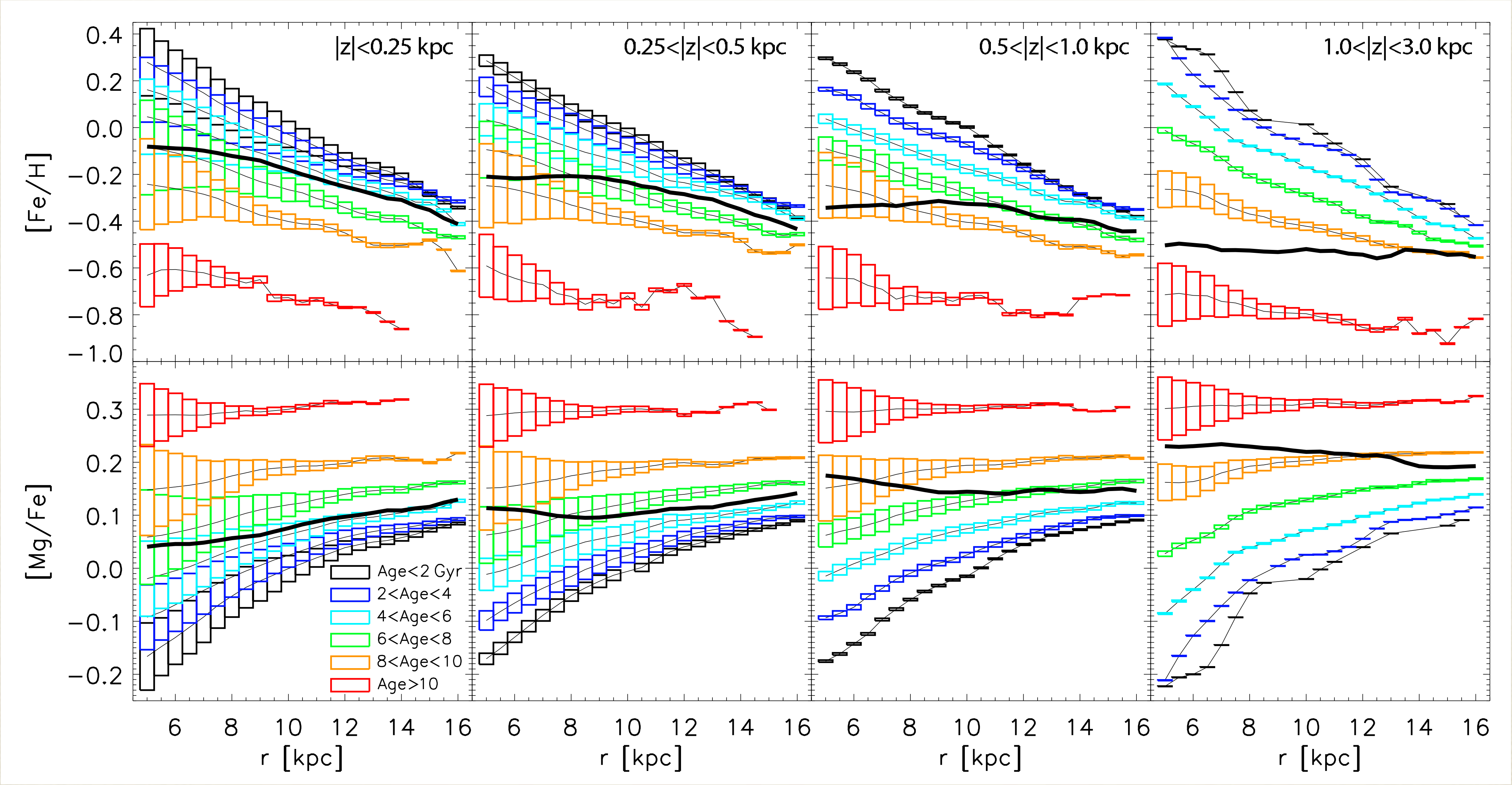
- Gas migrates similar to stars.
- The effect of inward and outward flows mostly cancel out.

The radial metallicity gradient



Minchev, Chiappini & Martig (2014)

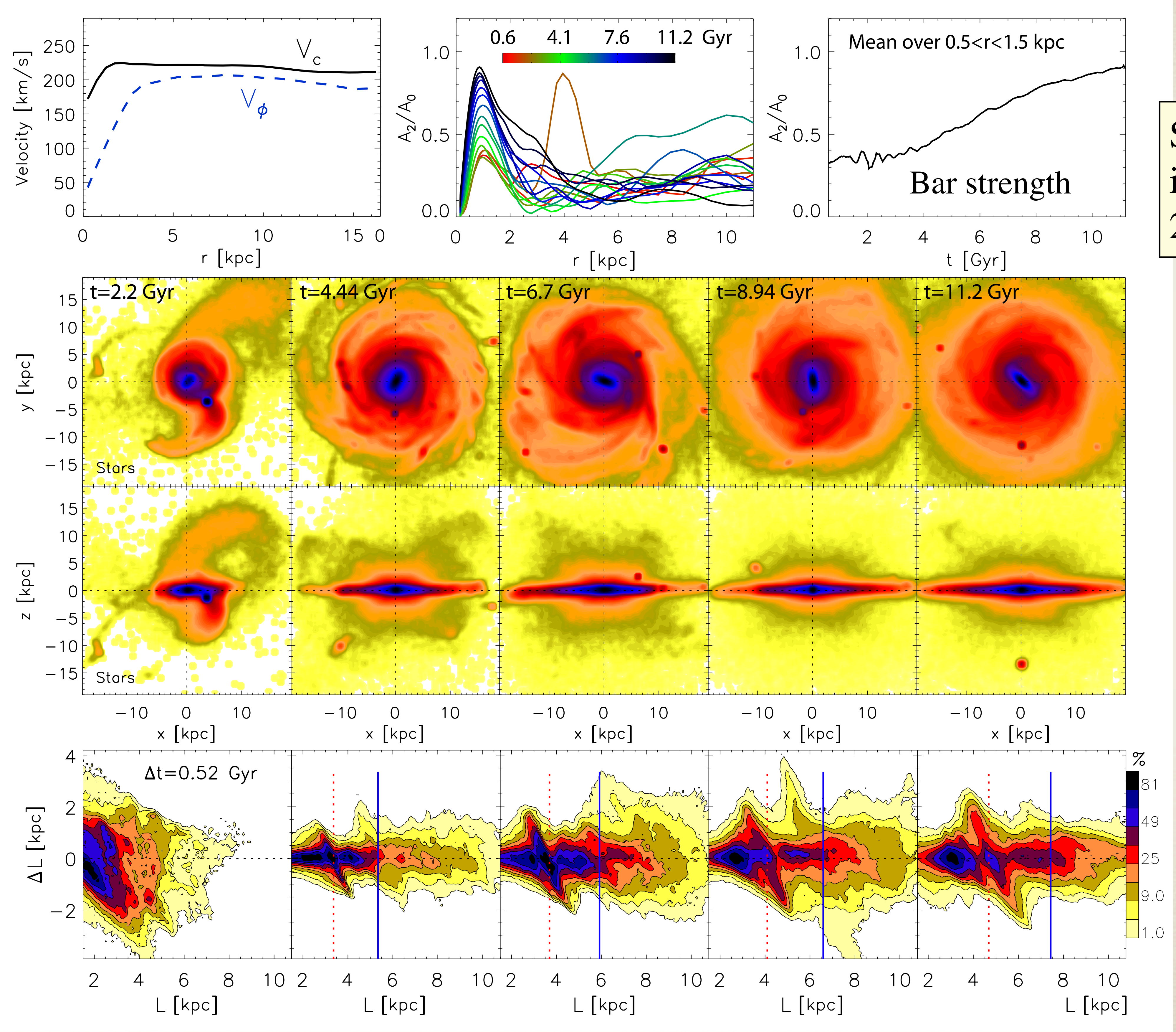
The radial metallicity gradient



Minchev, Chiappini & Martig (2014)

Interplay among different age groups is important.

Disk evolution in the cosmological context

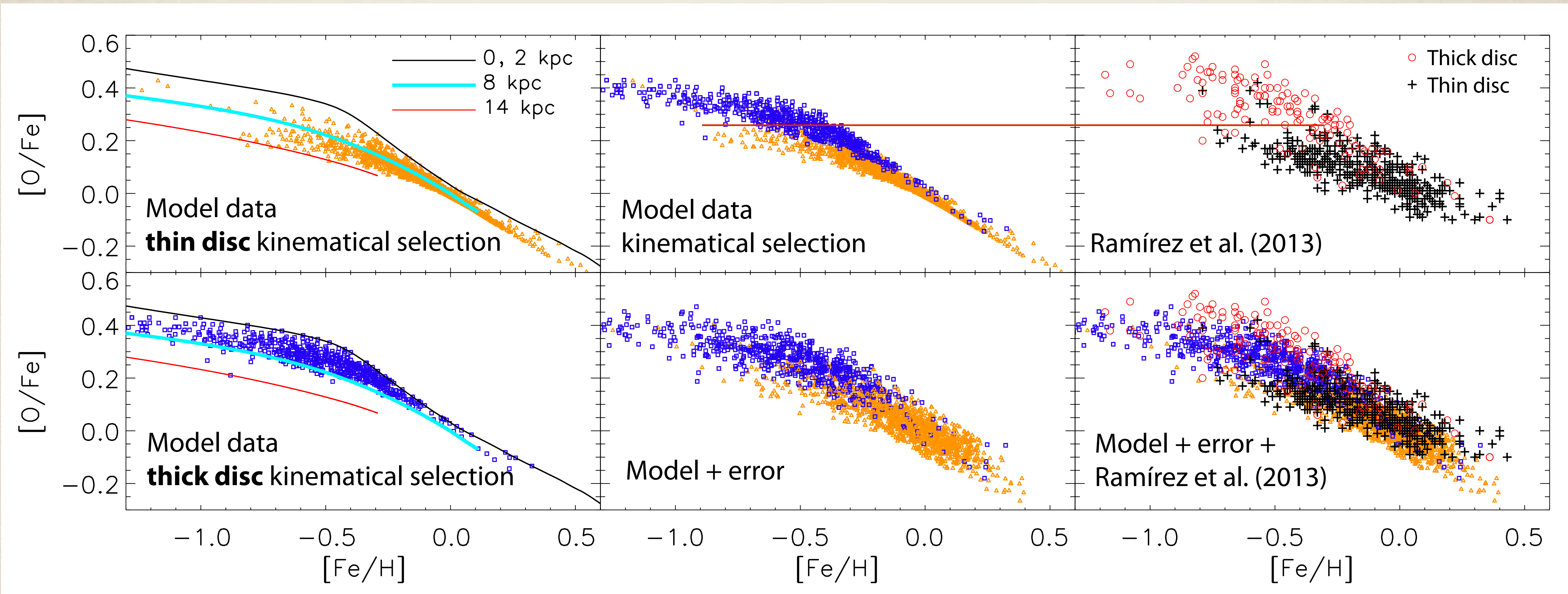


Simulations described in Martig et al. (2009, 2012)

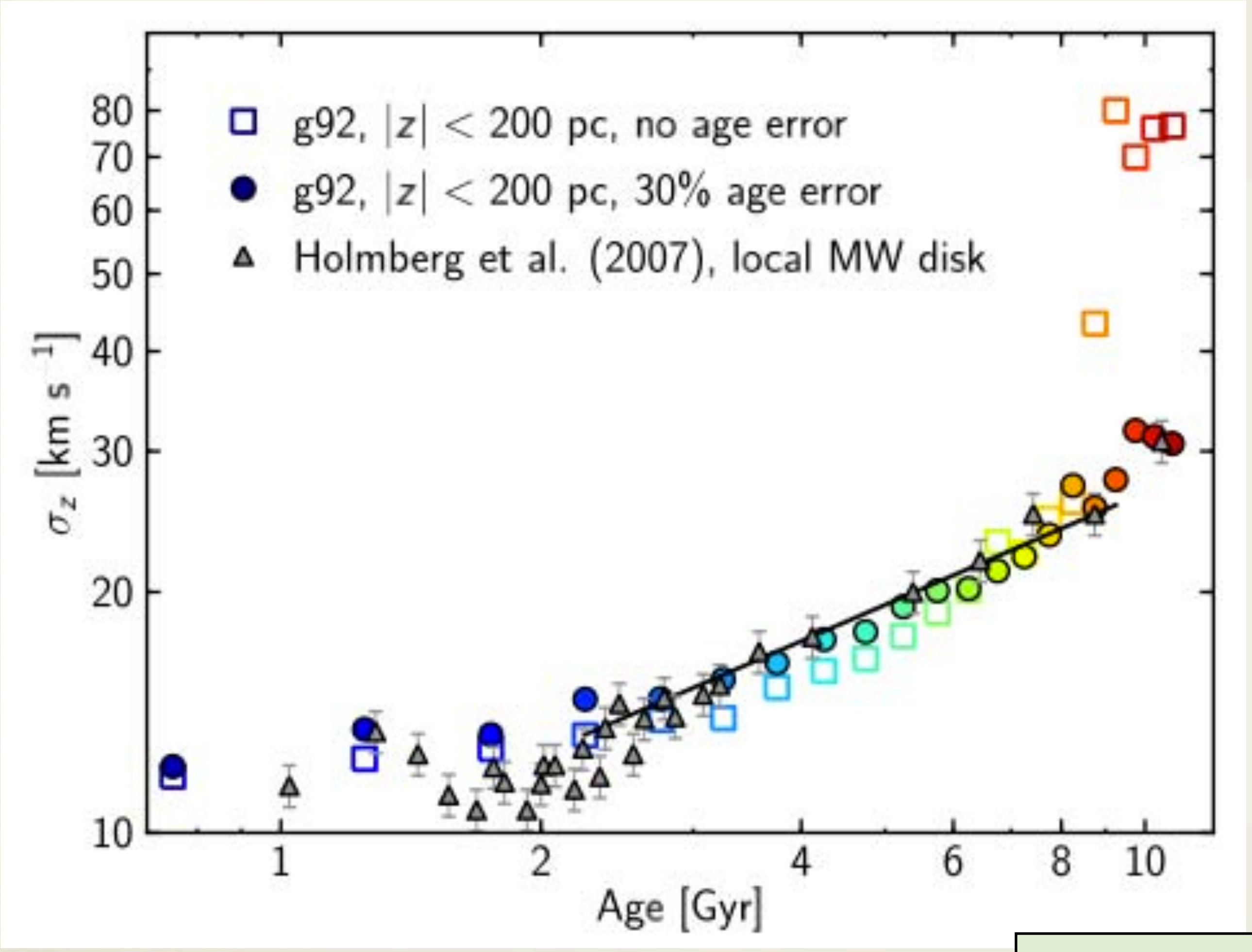
The [Fe/H]-[O/Fe] relation

Model kinematical selection

Ramírez et al. (2013) data



The age-velocity relation

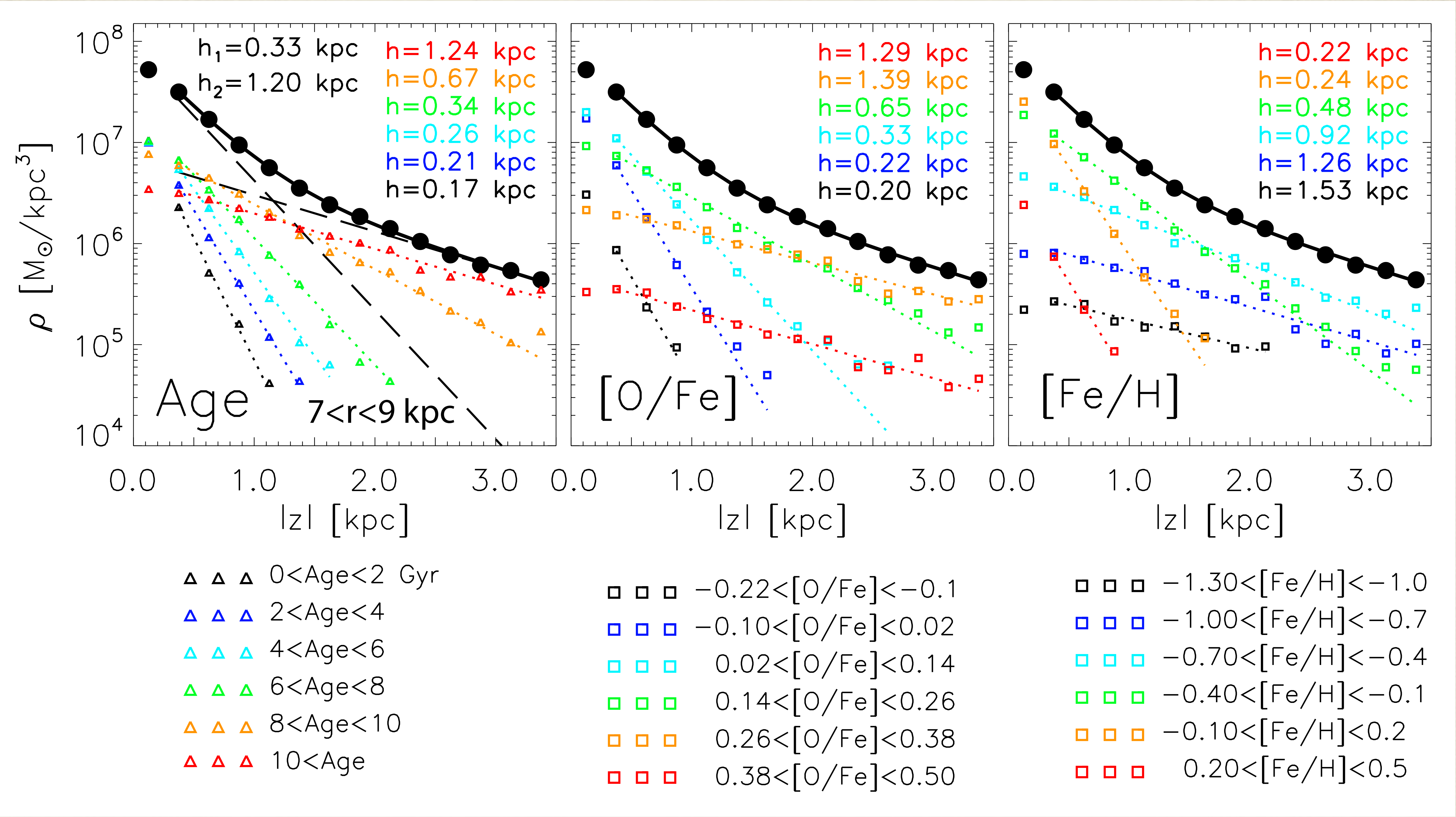


Step at 10 Gyr due to strong mergers.

Erased when 30% age errors convolved into simulated data.

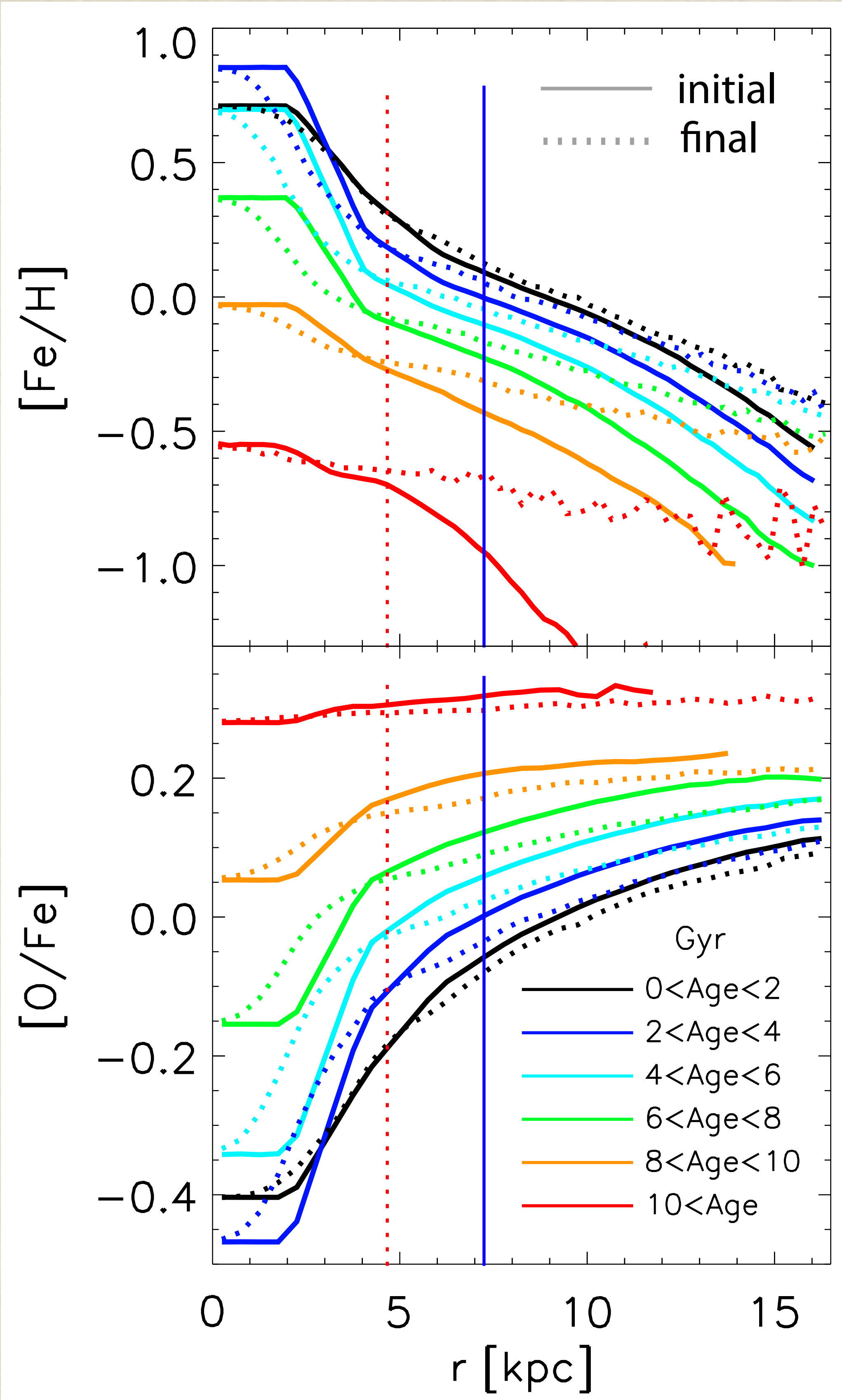
Martig, Minchev and Flynn (2014b)

Vertical disk scale-heights



- Thick disk from stars with ages > 8 Gyr, [O/Fe] > 0.15 dex and [Fe/H] < -0.7 dex

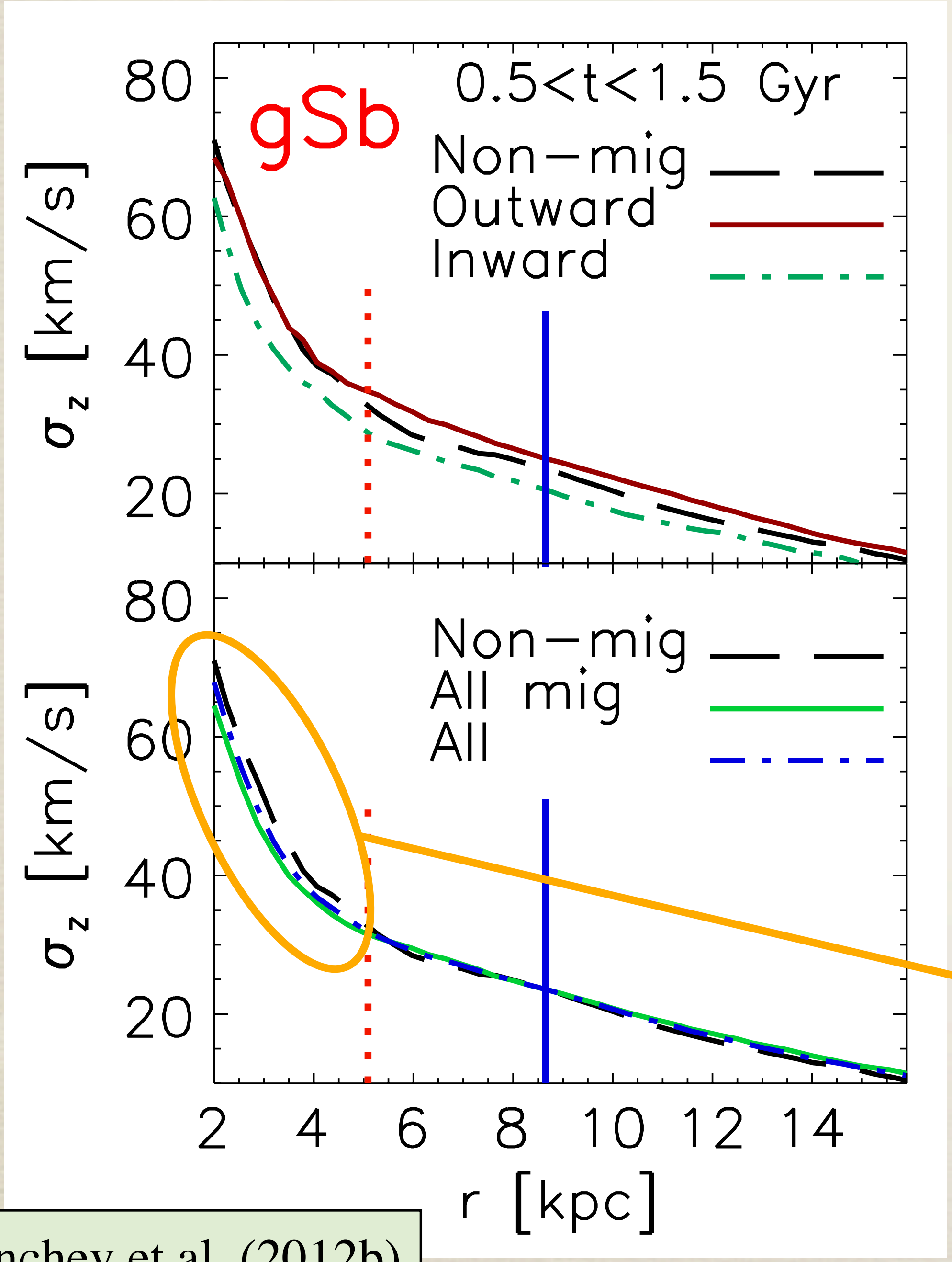
The effect of migration on the chemical gradients



- Strong impact on the old stars
- In the last 2 Gyr gradients almost unaffected
- Bar corotation acts as a pivot point

Migrators' contribution to the disk velocity dispersion in the absence of mergers

Vertical velocity dispersion



Minchev et al. (2012b)

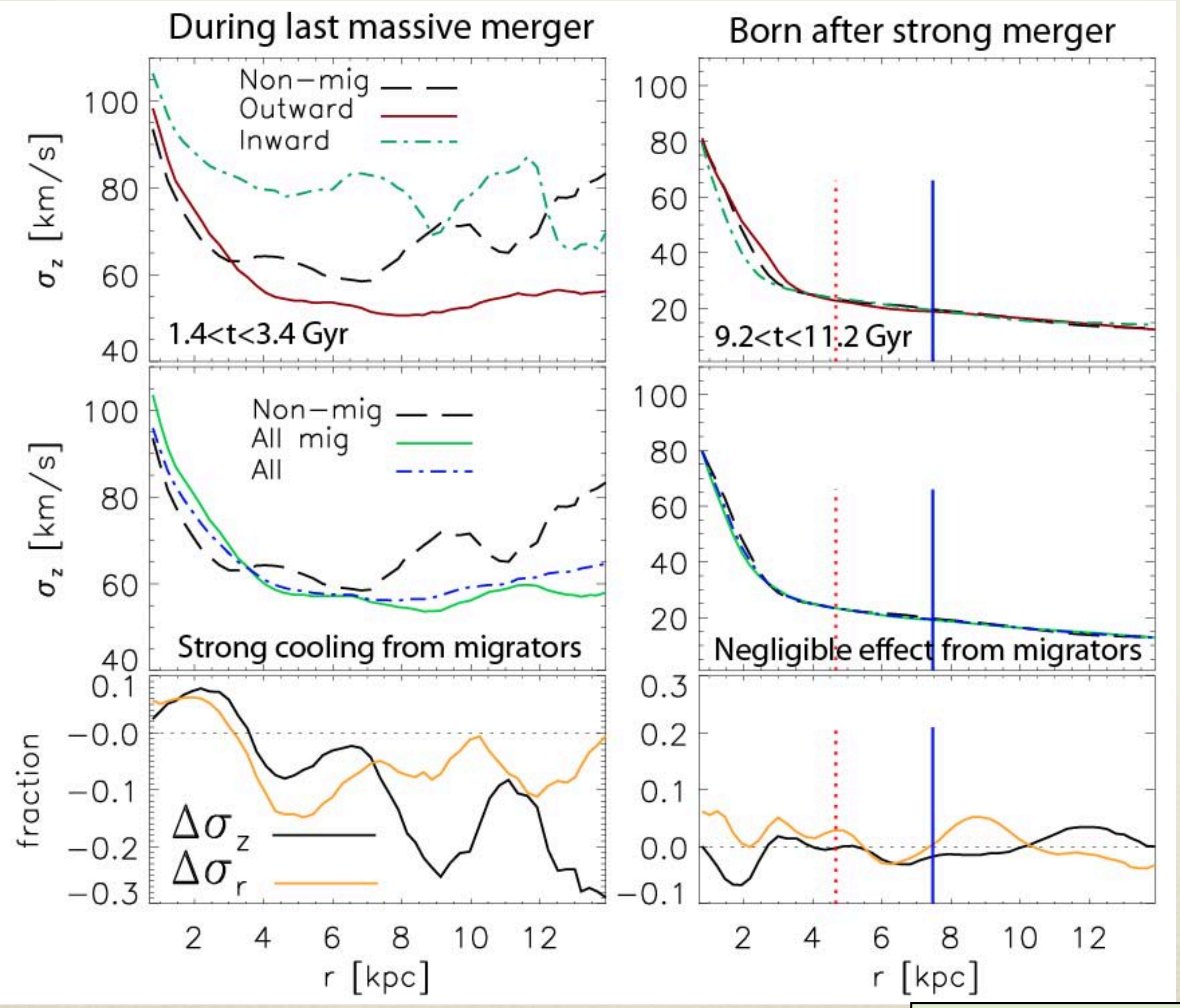
- Some increase in velocity dispersion from outward migrators.
- Some decrease in velocity dispersion resulting from inward migrators.
- Negligible overall effect to disk thickening.

Vertical disk cooling!

Migration cools the disk during mergers

Migration works against disk flaring

No effect on the vertical velocity dispersion.



Minchev, Chiappini and Martig (2014)

Conservation of vertical action

Vertical and radial actions conserved if:

- Vertical motion decouples from the radial motion
- Stars migrate (change guiding radii) slower than vertical and epicyclic oscillations.

Then $$J_z = E_z/\nu = Const.$$

Vertical energy (E_z) — Vertical epicyclic frequency (ν)

From Gauss' law and Poisson's equation $$\nu \sim \sqrt{2\pi G \Sigma},$$

$$\Sigma \sim \exp(-r/r_d) \longrightarrow \nu(r) \sim \exp(-r/2r_d)$$

Therefore, to preserve vertical action $$\langle E_z \rangle \sim \sigma_z^2 \sim \exp(-r/r_d)$$